The Industrial Metabolism of Plastics

Analysis of Material Flows, Energy Consumption and CO_2 Emissions in the Lifecycle of Plastics

Louis Joosten

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Het Industrieel Metabolisme van Kunststoffen

Analyse van materiaalstromen, energieconsumptie en CO_2-emissies in de levenscyclus van kunststoffen

(met een samenvatting in het Nederlands)

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Table of Contents

Chapter 1

Introduction

This thesis deals with the industrial metabolism of plastics. The term ‘Industrial Metabolism’ refers to the physical economic system of production and consumption, in which materials flow via complicated patterns. The aim of this thesis is to analyse the flows of plastics in the industrial society as well as the energy requirements and CO_2 emissions involved. This must lead to a better understanding of the possibilities to reduce the consumption of materials and energy, as well as the CO_2 emissions that are associated with the consumption of plastic products.

1.1 Background

Since the 1970’s the consciousness has grown that human activity largely influences the environment. In 1972 the report of the Club of Rome ‘The limits to growth’ (Meadows *et al.*, 1972) concluded that, if society would go on like it had done until then, natural resources of materials and fossil fuels would be exhausted within a few decades. In the following years the world was jolted awake to the importance of energy by two oil price shocks.

Because natural resources of fossil fuels have since shown to be much larger than the estimates made in 1972, the general opinion has risen that the exhaustion of natural resources is not an urgent problem. Although some experts still suggest that the bulk of the world's oil and gas has already been discovered and that declining production is inevitable, others believe that substantial amounts of oil and gas remain to be found and, furthermore, that unconventional sources will eventually be exploited (WEA, 2000). However, there will remain a large discrepancy between the very long time in which fossil energy carriers are produced in nature and the rapid consumption in our society. Even though in the short term no shortage is to be expected, it is clear that current energy consumption patterns are far from being sustainable (WEA, 2000).

As environmental science developed, society learned more about the relation between human activity and environmental impact. Whereas concern about the exhaustion of natural resources has declined, other environmental issues connected to the use of fossil fuels have come to the foreground. Apart from oil spills and other calamities that are connected to the use of fossil fuels, it is especially the emissions from fossil fuel combustion that are believed to have the largest impact on the environment via smog forming, acidification and climate change, as well as other emissions, e.g. small particulate matter and mercury from coal combustion.

With the increasing consciousness that developments in the economy lead to growing environmental impact, people became worried about the future of mankind. In 1987 the United Nations World Commission on Environment and Development published the report 'Our common future' (WCED, 1987). In this report they introduced the concept of 'sustainable development', which they defined as: *"a development that ensures the needs of the present generation, without compromising the ability of future generations to meet their own needs"* (p.8). The concept of sustainable development seeks a beneficial long-term development in terms of economic, social and environmental issues. Focussed on environmental issues, main objectives of sustainable development are the sustainable use of natural resources, safeguarding human health, preserving biodiversity and maintaining the ecological equilibrium. The latter includes, among others, the reduction of emissions of greenhouse gasses (GHGs).

Currently, one of the main environmental problems is global climate change, caused by an increase op the greenhouse effect, due to an increase of the concentration of GHGs in the atmosphere caused by anthropogenic GHG emissions. The greenhouse effect is a popular term for the effect that certain variable constituents of the Earth's lower atmosphere have on the infrared radiation on Earth and on the resulting average surface temperature. As incoming solar radiation strikes the surface of the earth, the surface gives off infrared radiation. This infrared radiation is absorbed and re-emitted by the so-called greenhouse gasses in the atmosphere, preventing it from escaping into space immediately. Consequently, in the long term an increase in the concentration of greenhouse gasses in the atmosphere is followed by an increase in the average surface temperature.

In their Third Assessment Report the UN Intergovernmental Panel on Climate Change (IPCC) concludes that 'an increasing body of observations gives a collective picture of a warming world and other changes in the climate system'. They observe that the global average surface temperature has increased over the twentieth century by about 0.6°C. This seemingly low increase is resulting in a significant decrease of the earth's snow cover and ice content and a considerable rise of the average sea level. They also conclude that 'there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities' (IPCC, 2001).

Carbon dioxide (CO_2) is one of the most important anthropogenic GHGs with respect to the volumes emitted, the CO_2 concentration of the atmosphere, the atmospheric lifetime of CO_2 and the infrared absorption cross section of CO_2. According to the IPCC (2001) the CO_2 concentration in the atmosphere has increased by 31% since 1750 and by approximately 20% during the past century. This increase is partly due to fossil fuels combustion and partly due to land-use changes, especially deforestation. Also the concentration of other greenhouse gasses, like methane (CH_4) and nitrous oxide (N_2O) have increased considerably.

Meanwhile about 190 countries have signed the United Nations Framework Convention on Climate Change. The ultimate objective of this convention is to achieve stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The Parties to this convention have agreed to protect the climate system for differentiated responsibilities and respective capabilities. Also it was agreed that the Parties should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate adverse effects (UNFCCC, 1992).

Most countries also adopted Agenda 21, a programme of action for sustainable development world-wide (UNCED, 1993). One of the programme areas of Agenda 21 is 'focusing on unsustainable patterns of production and consumption', in which it is stated that special attention should be paid to the demand of natural resources generated by unsustainable consumption and to the efficient use of those resources consistent with the goal of minimising depletion and reducing pollution. Another program area is 'developing national policies and strategies to encourage changes in unsustainable consumption patterns' in which is stated that achieving the goals of environmental quality and sustainable development will require greater efficiency in the use of energy and resources and minimisation of the generation of wastes.

1.2 Research on energy consumption and material flows

The consumption of fossil fuels is accompanied by a number of problems, including the exhaustion of non-renewable natural resources and the emission of greenhouse gasses. In order to combat these problems, many measures have been investigated during the last decades that aim at reductions of fossil fuels consumption. To reduce the emission of greenhouse gasses, initially measures were mainly looked for within the energy system. Later on, also the materials system was investigated to assess emission reduction measures (Worrell *et al.*, 1997).

1.2.1 Options for reducing fossil fuels consumption in the energy system

Since the 1970's, much research has aimed to find measures to reduce fossil fuels consumption in the energy system, especially in two areas:

- Energy efficiency improvement. This comes down to 'doing the same with less energy'.
- Development of other energy sources, including renewable sources like hydropower, solar, biomass and wind energy. This means: 'doing the same with less polluting energy sources'.

The potential of these directions has been studied intensively during the last decades. In particular with respect to energy efficiency improvement many measures have already been implemented, and new technology developments provide new opportunities today and in the future (see *e.g.* De Beer, 1998). At the same time, total consumption of fossil fuels has been growing steadily during the last decades, due to the growth in population and the increased levels of economic activities (Price *et al.*, 1998). Assuming business-as-usual, it may be expected that the rise of fossil fuel consumption will continue. Considering the finiteness of natural resources, in the long term renewable energy sources are obligatory to keep society going. However, new renewable energy technologies are still under development. It is not to be expected that renewable energy sources will be able to supply a large part of global energy consumption within the coming decades. So for the time being, fossil fuels are indispensable to satisfy a large part of society's energy demand. However, as indicated in Agenda 21 (UNCED, 1992), it is our responsibility to use fossil fuels in moderation.

1.2.2 Improvement options in the materials system

In 1995, about 40% of the global energy use was consumed by the industrial sector (Price *et al.*, 1998), to produce materials and products. This means that a large amount of energy generated by fossil fuels is consumed by the *materials system*. In addition fossil fuels are used as feedstock for the production of a number of chemical materials.

Until recently, studies investigating options to reduce fossil fuels consumption and GHG emissions mainly focused on changes in the *energy system*. Where industrial processes are concerned, most studies have assessed the question how the current materials system can be maintained using less energy.

There are, however, two reasons why improvements in the material system itself lead to a decreased consumption of fossil fuels as well. In the first place, if less materials are used, less materials have to be produced, so less energy is required for materials production and waste processing, and hence less CO_2 is emitted. In the second place, as indicated, part of the fossil fuels are used as feedstocks for synthetic organic materials, like plastics, paints, solvents and surfactants. A more efficient use of these materials directly leads to a decreased consumption of fossil fuels, reduced solid waste production and reduced atmospheric emissions throughout the lifecycle of these materials (see *e.g.* Patel, 1999).

In relation to materials use, there are three ways to improve the long-term materials productivity (Ayres *et al.*,1996). The first is to reduce dissipative uses of non-biodegradable materials. The second is to re-design products to use less material or design for re-use or recycling, and thirdly, to develop much more efficient technologies for material conversion

and recycling, to reduce or eliminate the need to extract virgin materials from the environment.

Inventory studies show that large reductions of fossil fuels consumption and CO_2 emissions can be achieved by improvements to the materials system. Worrell (1994) concludes from case studies on plastic packaging and fertilisers that significant CO_2 emission reductions can be achieved by a more efficient use of materials. Hekkert (2000) found that by improved management of packaging materials, CO_2 emissions can be reduced cost- effectively with 40-50% in the nearby future. Patel (1999) studied a number of options to reduce CO_2 emissions from the German lifecycle of synthetic organic materials and found that a reduction of 24% can be achieved. Gielen (1999) concludes from extensive model calculations on the Western European energy and materials system that the potential for CO_2 emission reduction in the materials system appears to be of a similar order of magnitude as the emission reduction potential in the energy system. These examples demonstrate that it is worthwhile to study measures to improve the productivity of materials in order to reduce fossil fuels consumption and CO_2 emissions. Similar conclusions can be drawn to reduce the generation of wastes.

During the last twenty years, many technical measures have been investigated that are expected to contribute to a reduction of fossil fuels consumption, CO_2 emissions and the generation of wastes through improvements to the materials system. These measures include techniques for recycling (closing material cycles), good housekeeping, downgauging (making a given product with less material), product life prolongation and substitution (the use of alternative, more environmentally friendly feedstocks and materials).

To assess the potential of each measure, research is needed on the technical, socio-economic and environmental feasibility. Measures to improve fossil fuels consumption, emission reduction and the generation of wastes within the production system may have complex interactions with each other, as well as with consumption patterns. This demonstrates the need for a thorough analysis of the effects and consequences of different measures, to enable society to evaluate the measures and make sound policy choices.

For simple measures, like good housekeeping and product life prolongation, it is rather easy to assess the results of implementation. Because they only influence specific parts of the materials system, their influence on materials consumption, fossil fuels consumption and CO_2 emissions is generally limited. On the other hand, implementation of those measures is likely to be relatively easy. Measures that lead to more structural changes in materials system, like material recycling and substitution, may be much more difficult to implement, but they may be more powerful in reducing fossil fuels consumption, wastes generation and CO_2 emissions. However, because of their broad influence on the materials system, their exact impacts are not easy to estimate.

1.2.3 Industrial Ecology and the concept of Industrial Metabolism

For the assessment of the impact of measures on materials consumption, fossil fuels consumption, wastes generation and atmospheric CO_2 emissions, detailed understanding of the material system is needed. The whole lifecycle of materials has to be investigated, including all sectors of industry, with all their inputs and outputs.

Understanding of the materials system is one of the major goals of a research discipline called 'Industrial Ecology' (IE), the science that studies processes in the physical economy in analogy to the study of the (physical) environment (Van der Voet *et al.*, 2000). IE uses a systems-oriented approach to the environmental problems within the economic system. With respect to industrial activities IE suggests that design and manufacturing processes are influenced by its surroundings, and should not be evaluated in isolation (Graedel, 1994). This systems approach can be used to optimise the total resource cycles in society, including energy, materials and capital, or, in other words, to improve the productivity of resources (Frosch, 1994, Socolow, 1994).

Industrial Ecology builds on the concept of Industrial Metabolism, which was defined by Ayres *et al.* (1989). The concept of Industrial Metabolism argues the analogy between biological organisms and the economic system, both of which are materials-processing systems driven by a flow of free energy (Ayres *et al.*, 1994). However, there is one major way in which the industrial metabolic system differs from natural metabolism: whereas in the biosphere processes are attuned to such a degree that waste generated in one process is converted into a resource for another, in the economy resources are squandered, thus creating both depletion and pollution problems (Ayres *et al.*, 1994, Van der Voet *et al.*, 2000). Industrial Metabolism states that, by taking lessons from the biosphere, economic processes can be improved and attuned to minimise losses to the environment. The analogy between natural metabolism and industrial metabolism is intended to be a guideline for seeking ways to achieve a sustainable steady-state industrial economy.

Within the concept of Industrial Metabolism it is important to understand the flow (or metabolism) of materials through the economy, starting with the extraction of natural feedstocks, followed by the production of materials, the manufacture of products, and finally the customer product cycle. This is studied by Material Flow Analysis (MFA). Material Flow Analysis, which is also referred to as Material Flow Accounting, is based on the Law of Mass Conservation (Fischer-Kowalski *et al.*, 1999). The MFA approach is used to construct materials balances of specific materials or chemical elements within the economic system (*e.g.* studies of chlorine (Ayres *et al.*, 1996), (Tukker *et al.*, 1995), (Kleijn *et al.*, 1997) and

heavy metals (Lohm *et al.*, 1994), (Van der Voet *et al.*, 2000))[1]. Usually an MFA is confined to material flows within a specific geographical region in a certain period of time.

MFA builds on the field of the analysis of energy flows. But MFA is more complicated (Socolow, 1994). Generally, there is no interest in an energy flow beyond the point of use, where energy is usually degraded into heat. MFA generally continues beyond this point of use, as the products of material use may result in environmental damage. The methods used for MFA also owe a lot to the LifeCycle Analysis (LCA) methodology, that stems from the 1980's. In a LCA all environmental impacts of specific products are mapped and compared, by analysing the production routes and investigating all environmental aspects of the production processes involved (Fava *et al.*, 1991, Keoleian *et al.*, 1993).

Material Flow Analysis can help to identify and analyse opportunities for increasing resource productivity. When combined with emission analysis, Material Flow Analysis can help to identify those areas that need attention for pollution prevention.

1.3 Scope and objective of this thesis

This thesis deals with the research question:

Which are promising options for decreasing material consumption, energy consumption and CO_2 emissions in the lifecycle of plastics?

To answer this question a calculation method is developed, that brings together material flow analysis, energy analysis and emission analysis. This method is used to analyse the lifecycle of plastics in The Netherlands and the material and energy inputs, CO_2 emissions and costs that are involved.

Subsequently, we study options to improve the resource productivity of plastics and its feedstocks. Plastics are mainly made of fossil fuels, which directly links the concepts of energy and material flow analysis. It links material flows to such problems as global climate change and the long-term exhaustion of non-renewable resources (see above). The productivity of the materials cycle of fossil feedstocks can be improved through increased energy efficiency as well as increased efficiency with which we use materials (*i.e.* plastics).

A number of measures is investigated, that aim to improve the efficiency fossil fuels use and the reduction of CO_2 emissions in the lifecycle of plastics. Emphasis is on those options that aim at improved material management, rather than changes in the energy system, as those

[1] The analysis of specific elements or chemical compounds is also referred to as Substance Flow Analysis (SFA).

have been discussed by others in previous studies (*e.g.* Worrell, 1994 and De Beer, 1998). Changes in the materials system often involve the use of alternative technologies. In this thesis both existing technologies and technologies that are under development are explored.

1.4 Outline of this thesis

The lifecycle of materials consists of a number of stages, from raw materials extraction, via materials production, the manufacturing of products, consumption, discarding and finally recycling or other waste treatment. Material Flow Analysis investigates all stages, in order to get detailed and complete information on material flows through society.

Chapter 2 deals with the question how material flows through society can be measured. To conduct material flow analysis, it is often very hard to find reliable and consistent data on the production and consumption of materials, products and waste. Data on disaggregated levels and especially data on flows of materials that are part of products, or that are used to pack products, is hard to find. Furthermore, because of differences between aggregation levels, reference years and definitions, it is not easy to relate data from different data sources. In order to overcome these problems, in Chapter 2 the so-called STREAMS method is presented. This calculation method essentially draws data from one data source, the so-called supply and use tables, made by national statistical offices. With this method material flows in all stages of the lifecycle can be analysed, including the stage of final consumption, for a consistent period.

In Chapter 3 the STREAMS method is tested and applied to assess all stages in the lifecycle of plastics in The Netherlands. Especially final consumption is analysed in detail, making a clear distinction between plastics used as final products, as product parts and as packaging materials. Product parts and packaging materials that cross the national border via exports and imports of products are accounted for. From the results of the STREAMS method a material balance of plastics in The Netherlands' economy is constructed.

In all stages of their lifecycle, feedstocks and materials go through (industrial) processes that convert them from one state into another. The aim of Chapter 4 is to investigate all processes in the lifecycle of plastics with respect to the material inputs and outputs, energy inputs and outputs and emissions that are involved. Successively, technology explorations are conducted for crudes extraction, feedstocks production, alkenes production, intermediates production, plastics production, plastics processing and plastic waste processing. In these technology explorations, energy consumption and CO_2 emissions per unit of product are assessed. The results are used to calculate the total annual energy consumption of and the total annual CO_2 emissions from the Western European lifecycle of plastics. This gives insight into the contribution of the plastics lifecycle in total Western European energy consumption and CO_2

emissions. It also gives insight into the relative importance, with respect to energy consumption and CO_2 emissions, of the different processes that constitute the lifecycle of plastics.

Chapter 5 is concerned with the question which structural changes in the lifecycle of plastics can be used to reduce the consumption of fossil fuels and the emissions of CO_2. A method is developed and used to assess the sensitivity of the lifecycle, with respect to fossil fuels consumption, CO_2 emissions and costs, for implementing structural changes aiming to reduce fossil fuels consumption and / or CO_2 emissions. Those measures come down to the introduction of new technologies to replace existing processes, or changes within or between existing processes. As far as existing processes are concerned, the results of the technology explorations from chapter 4 are used. For new technologies that are currently under development, new technology explorations are conducted in this chapter. From the results of the analysis conclusions can be drawn on the potential impact of the different measures, with respect to their influence on total fossil fuels consumption, total CO_2 emissions and total costs of the lifecycle of plastics.

In Chapter 6, the last chapter of this thesis, a summary is given of the results of the previous chapters and major conclusions are drawn. Finally, suggestions for further research are given.

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Chapter 2

STREAMS: A New Method for Analysing Material Flows through Society[1]

Abstract

For the development of material, product and waste oriented policies, knowledge about the flow, use and disposal of materials through society is necessary. The risks of taking policy measures leading to suboptimum solutions of environmental problems call for an integral survey of material flows through society. However, up to now integral analyses of physical material flows are lacking. Problems like differences in definitions, in subdivisions of flows and in reference years, make it difficult to relate data from different sources to get an overall view. In this chapter STREAMS, a new method to calculate physical material flows through society, is proposed. The method is based on the so-called supply and use tables, which describe a country's economy in terms of supply and use of materials, products and services by industries, service sectors and consumers. In our approach materials and products are tracked on their way from extraction of raw materials to the final consumption of products and beyond, into the stage of waste. The method has the advantage of deriving almost all data from one source. In this article the method is described. In a separate study the method is applied to obtain an integral survey of the flow of plastics through The Netherlands, showing that the method can be used to assess the final materials consumption on a highly detailed level.

[1] Published as: Joosten, L.A.J., Hekkert, M.P., Worrell, E., Turkenburg, W.C.: *STREAMS: A new method for analysing material flows through society*, Resources, Conservation and Recycling 27 (3), 1999, pp. 249-266.

2.1 Introduction

Traditionally, materials use is summarised as extraction of raw materials from the environment, using them for a certain purpose and finally discarding and returning them to the environment in the form of waste. Because of the growth of the earth's population, the need to improve the standard of living in developing countries and the overall increase of consumption, there is a growing demand for raw materials. As a result, various problems become obvious, e.g. the exhaustion of limited resources, the emission of pollutants to the environment and the production and disposal of waste. Materials are used to deliver services to fulfil a variety of human needs. For a sustainable use of resources it is essential to use these materials more efficiently, which can be achieved by decreasing the amount of materials needed per unit of service or extending the period in which materials are being used. In the past a lot of effort was put into 'end-of-pipe' measures, such as separation and incineration of wastes. Nowadays it becomes more and more clear that these measures are not sufficient to ensure the sustainability of materials use. For that purpose, attention should also be given to product design (design for recycling), the selection of materials and the design of the manufacturing processes.

To be able to improve the efficiency of raw materials use, knowledge about the flow of these materials through society, at all stages of their lifetime -'from cradle to grave'- is a prerequisite. Therefore, an integral analysis of these material flows is needed. However, reliable data for this analysis is generally very hard to be found. In a previous analysis of the potential of material efficiency improvement in the use of packaging (Worrell *et al.*, 1995), it was found that comprehensive data on disaggregated levels about the use of materials in various functions and products is lacking. In literature, assessments of material flows through society mostly concern specific stages in the lifetime of materials: most studies focus either on production figures or on waste figures. In trying to relate these assessments to get an overall picture, the problem arises that every author, often implicitly, uses his own approaches, definitions, reference years and subdivisions of material flows. Given these problems, it is concluded that a new approach is needed to allow integrated mapping of material flows through society.

From an environmentalist's point of view the most interesting issue, when mapping the amount of materials circulating in society, is the input of raw materials that is needed to keep the system going. National statistics about the use of materials can provide an impression of this input. However, because of imports and exports, the use of raw materials in a country does not say much about the amount of raw materials that is finally consumed in that country. In this study we are especially interested in the amount of materials that enter the stage of *final consumption.* The stage of final consumption is the essential phase in the life of

products, as in this stage they provide the services they were produced for. The demand for services, together with the material intensity per unit of service, can be seen as the engine that drives the system of material flows through society. After final consumption the products turn into waste. The materials they contain may, however, be recycled and be used to produce other products.

Unfortunately, there is an almost complete lack of direct information about the final consumption of products. Frequently a country's *apparent consumption* of a certain product, calculated as production plus imports minus exports, is used as an estimate for its *final consumption*. However, this estimate only holds for *final products*, which are not processed further and which are not used as packaging or as component. For materials and intermediate products, apparent consumption rather means 'the use in industry'. They change hands one or more times before reaching the final consumer, so in this case the *apparent consumption* is not a very good estimate for the *final consumption*. Apart from that, imports and exports of packaging and components, together with the goods they are applied to, are invisible in statistics, so they can not be tracked directly.

Given all these problems and limitations, we developed a new method to map and quantify the material flows through society on a disaggregated level. In this article, this method, called STREAMS (*STatistical REsearch for Analysing Material Streams)*, is presented. The method is based on the use of economic statistic data. Within STREAMS, much attention is paid to the assessment of the *final consumption* of packaging and components.

In section 2.2 the STREAMS method is described in detail. In section 2.3 some methodological aspects are discussed. In section 2.4, conclusions are drawn on the abilities of the method, partly based on the results of case studies which are published in separate articles (Chapter 3 and Hekkert *et al.,* 2000). Finally, recommendations are made for further refinement and testing of the method.

2.2 Methodology

In this section the STREAMS method is described. The method is based on the use of economic *supply and use tables*, which provide an overview of a country's material flows in monetary terms. These tables are compiled annually by the national statistical offices of a number of countries, including The Netherlands and Germany. The tables present a total description of the economy of a country in terms of the supply and use of goods and services by the industries as well as the consumers. Also figures about imports and exports are included. Although the level of detail of these tables varies considerably between countries, they contain a lot of information that can be used to analyse the flow of materials through society.

Before proceeding, some definitions have to be made clear. We use the term ‘materials’ to indicate substances, which have no clearly defined form. Examples are: ores, oil, plastic granulate *etc*. Objects that have a defined form (tangible objects) are called ‘products’. Mind that we use a narrow definition of the term ‘products’: in our terminology, materials and services are not called ‘products’, although they are ‘produced’ by certain industries or service sectors. ‘Materials’ and ‘products’ together are called ‘goods’ or ‘commodities’. The delivery of ‘goods’ or ‘commodities’ involves substance flows, in contrast to the delivery of ‘services’, for which the accompanying substance flows are negligible.

In paragraph 2.2.1, we present a schematic representation of material flows through society. In paragraphs 2.2.2 and 2.2.3 the STREAMS method is described in detail. The method consists of two parts. In paragraph 2.2.2 we describe the first part, the ‘supply and use analysis’, in which the main material flows are mapped relatively straightforwardly from the supply and use tables. The analysis results in data on the supply and the *direct use* (apparent consumption) of goods. The second part, the ‘final consumption analysis’, which is described in paragraph 2.2.3, consists of a calculation method for the *final consumption* of products.

2.2.1 Schematic representation of material flows through society

In the STREAMS method material flows through society are modelled as shown in Figure 1. In this figure material flows are represented as arrows between boxes. Boxes represent processes. Each flow can be composed of several subflows, representing various (sub-)types of materials or products. Each process can be broken down into various types of processes or into various industries by which the process is conducted.

The main direction of the material flows in Figure 1 is from the top to the bottom. On this route materials pass through several phases of their lifecycle. They enter as *raw materials*, in the form in which they were extracted from the environment. In the first operation, the *materials production* operation, they are converted into *intermediate materials*. Intermediate materials are e.g. primary plastics for injection moulding, or pulp for paper production. In the *materials processing* operation the intermediate materials are processed into products. Three types of products are discerned: packaging, components and final products.

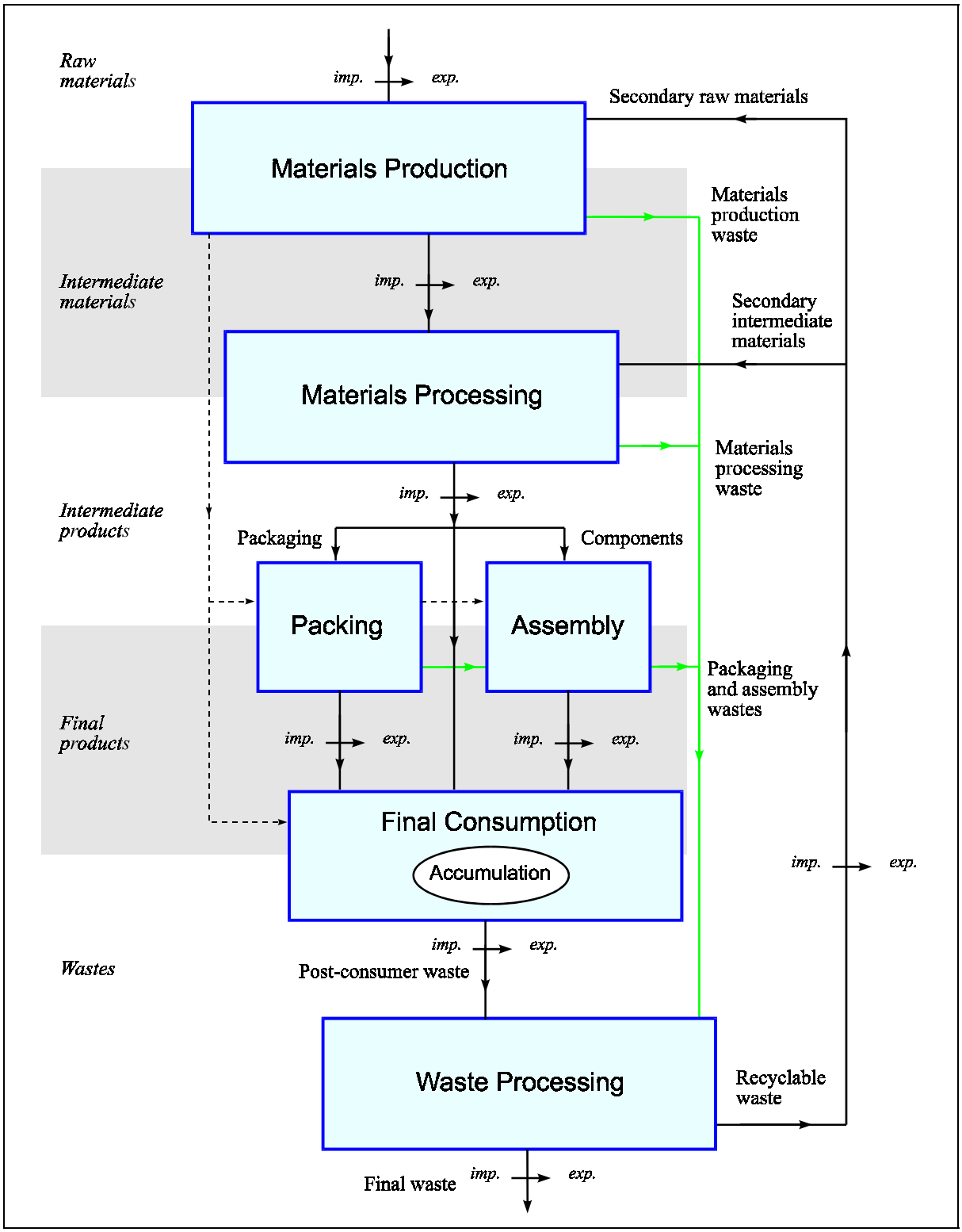

Figure 1 Schematic representation of material flows through society.

Final products are already suitable for final consumption; they need no further processing step. *Packaging* and *components* are *intermediate products*: they need a packing or assembly

operation respectively before reaching their final consumers. The industries that use packaging to pack their products and the industries that use components to assemble them to their goods are *not* the *final consumers* of those packaging and components. In contrast, the (final) consumers (*e.g.* households, industries and exports) of the goods they produce are also the final consumers of the packaging and components, which come along with those goods. *There* the packaging and components eventually become waste.

Final consumers discard products in the form of *post-consumer waste*. The materials production, materials processing, packing and assembly operations described above bring about *production, processing, packaging and assembly wastes*, which, added to the post-consumer waste, form the total waste volume. A part of the total waste is recycled. The rest, defined as *final waste,* has to be incinerated or landfilled. The recyclable part can either be used as secondary raw material for materials production or as secondary intermediate material for materials processing, depending on the material and the recycling route followed[2].

Usually, materials flows research is conducted **for a specific material** or group of materials, *e.g.* plastics, wood or steel. In this article these materials are called *core materials.* Products that mainly consist of core materials are called *core products.* In this article, the main industries that produce or process core materials or core products are called *core industries*. This is done to distinguish them from the other materials, products and industries in the economy.

To use Figure 1 to map specific material flows **in a specific year**, stocks have to be taken into account. The largest stock exists in the stage of final consumption, representing the materials that are presently in use in the form of final products. Because the final consumption is subject to changes in time, the stock of materials in society changes too. In Figure 1 this stock is modelled as an accumulation process. In fact, stocks exist between all processing steps. However, in our approach, apart from the stock at the stage of final consumption, stocks are neglected, because they are relatively small and stable compared to the annual flow of materials[3]. The result of this assumption is that the total input of a process equals the total output (including waste), which would not be the case if stocks were included.

To use the model to map specific material flows in a specific year **in a specific country**, imports and exports of core raw materials, intermediate materials, packaging, components,

[2] Multiple use of packaging and components and reuse of final ('second hand') products are not discerned. In Figure 1 they stay in the final consumption stage until they are finally discarded.

[3] The use table contains a column 'stock mutation', which gives an indication of the relative importance of changes in stocks. From the use table of The Netherlands it can be concluded that for almost all products stock mutations are well beneath 5% of total use.

final products and wastes have to be taken into account, as well as (indirect) imports and exports of packaging around goods and components within all kinds of products.

So far, we have spoken about material flows between *processes*. However, in statistics *industries* are discerned instead of processes. In some cases several processes take place successively in one single industry. In that case processes do not become visible in statistics separately. For this reason virtual flows were added to Figure 1, indicated by dotted lines, apparently passing by the materials processing, packing and assembly processes.

2.2.2 The supply and use analysis

In this paragraph we describe the supply and use analysis to map **specific material flows in a specific country in a specific year** using the country's **supply and use tables**. As an example the supply and use tables for The Netherlands are schematically shown in Figure 2 (CBS, 1993). Depending on the aggregation level, in the supply and use tables a number of goods, services, industries, service sectors and final demand categories[4] is discerned. All figures are expressed in monetary units. Only commercial deliveries are mapped, so most of the waste flows are invisible, simply because they are not traded.

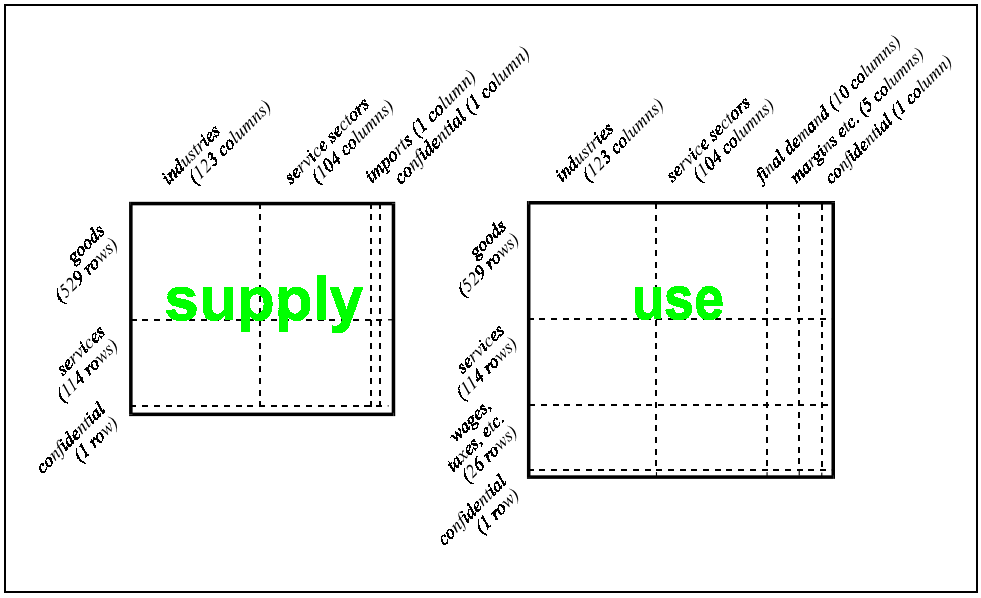

Figure 2 Outline the supply and use tables for The Netherlands as issued annually by Statistics Netherlands (CBS 1993).

In the STREAMS method, physical data on the supply and direct use (apparent consumption) of core materials and products is obtained in several successive steps, which will be described below. First, a *process scheme* of the material under investigation is constructed and *core*

[4] Mainly households

materials, *core* products and *core* industries are discerned (1). Next, core supply and use tables are assembled from the total supply and use tables (2). These monetary tables are corrected for confidential trade (3) and converted into physical units (4). Subsequently, the tables are corrected for intrasectoral trade (5). Eventually, after calculation of the core materials contents of core products (6), physical data on the supply and direct use (apparent consumption) of core materials can be derived.

(1) Construction of the process scheme and assignment of core materials, core products and core industries

A process scheme of the material under investigation is constructed to get an overview of the material flows and processes involved, using Figure 1 as a guideline. Core raw materials, core intermediate materials and core products are discerned. Also core materials production industries and core materials processing industries are discerned.

(2) Construction of core supply and use tables

Core supply and use tables **(S_c** and **U_c)** are constructed by extracting those rows from the supply and use tables **S** and **U** which represent the flows of the core materials and products in a specific year (in monetary terms).

(3) Correction for confidential supplies

As can be seen from Figure 2, some data on supplies and uses is kept confidential. In the supply and use tables these are collected in the column ‘confidential’. Statistical offices are obliged to keep some data out of publications if the material or product under investigation is manufactured by only a few companies, which do not want to see their turnovers published. If the *core* supply and use tables contain confidential supplies and uses, assumptions have to be made about the ‘confidential’ users and suppliers of core materials and products. For these assumptions, the row ‘confidential’ in the supply and use tables, showing the total confidential supplies and uses per industry, provides additional indications. With these assumptions, the core supply and use tables are corrected to represent the ‘true’ supplies and uses.

(4) Conversion of monetary data into physical data

A conversion of monetary data into physical data is needed to allow a physical analysis of material flows. This conversion can be done several ways. The highest accuracy is achieved if for all core materials and products mean prices per unit are used for each individual industry. However, in many cases, price information on this detailed level is not available. In some cases in the national statistics, e.g. the statistics of foreign trade[5] or

[5] In that case the assumption is made that mean exports prices match with mean domestic selling prices.

production statistics, average retail prices[6] can be found which are averages for the total national supplies of the core materials and products. If no such statistics are available, other data sources, e.g. market inquiries, have to be used to obtain mean prices of the core materials and products. In general, however, this will lead to less accurate results. By dividing the core supply and use tables ($\mathbf{S_c}$ and $\mathbf{U_c}$) by the mean prices of the core materials and products, physical core supply and use tables ($\mathbf{S_c}$* and $\mathbf{U_c}$*)[7] are obtained.

(5) Correction for intrasectoral trade

A correction for intrasectoral trade has to be made to the core supply and use tables, $\mathbf{S_c}$ and $\mathbf{U_c}$. Companies may buy a certain amount of their input and output core materials and products from colleagues within the same industry. These core materials and products appear in the supply and use tables both as supplies and as uses of the same industry. To correct for this, in the STREAMS method, for each industry the net use and the net supply of core materials and products are calculated.

(6) Calculation of the core materials content of core products

In general, core products do not entirely consist of core intermediate materials. They may contain all kinds of additives and they may be composed of several components, some of which are not made of core intermediate materials. This implies that the weight of core products is not directly a measure for the use of core materials. By analysing the material flows of the core material processing industries, it is possible to calculate the percentage of core intermediate materials in core products. In our approach this is done by comparing the outputs of core products with the inputs of core intermediate materials, taking into account the amount of core materials processing waste produced. Using this percentage, the supplies and uses of core products in the core supply and use tables are converted into their core intermediate materials content. Therefore, in our method, all weight figures for core products concern their intermediate materials content.

For some materials it may also be possible to calculate the core *raw* materials content. This depends on the availability of data on the supply and use of the core raw materials in the supply and use tables. In these cases the core raw materials content of core intermediate *materials* can be obtained by conducting a material flow analysis of the core materials production industries. The core raw materials content of core *products* can be obtained by subsequently conducting a material flow analysis of the core materials processing industries, as described above.

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[6] Because of value added by trade and transportation, purchase prices are not equal to retail prices. Purchase prices can be calculated from retail prices taking into account this value added, which can be found in a separate column in the (core) supply and use tables.

[7] Tables indicated with an asterisk (*) are expressed in physical units (kg or ktonnes), tables without asterisk are expressed in monetary units.

If the core supply and use tables are sufficiently detailed, it is possible to read from the physical core supply and use tables:

- the use of core raw materials;
- the supply of core intermediate materials;
- imports and exports of core intermediate materials;
- the use of core intermediate materials by the core materials processing industries;
- the use of core intermediate materials by other industries and consumers;
- the supply of core products (packaging, components and final products) by the core materials processing industries;
- the supply of core products by other industries;
- imports and exports of core products;
- the use of core products by industries, service sectors and households;
- the supply and use of core waste materials (as far as they are traded).

With the results obtained so far, physical amounts can be added to the material flows in Figure 1, as far as the ‘materials production’ and ‘materials processing’ stages are concerned.

2.2.3 The final consumption analysis

Above, only *direct* supplies and purchases were determined: supplies and purchases that can be read *directly* from the physical core supply and use tables. However, the direct purchases of packaging and components, as found in the core use table, do not specify their final consumption, because the industries that purchase them are *not* the final consumers. Packaging and components are used *indirectly*: they change hands once more before reaching their final consumer. In the STREAMS method packaging and components are assigned to their final consumers in the final consumption analysis, which is described in this paragraph.

The essence of the final consumption analysis is schematically represented in Figure 3. Each industry has its specific uses and supplies of materials and products. All materials and products that are used are bought with the aim of producing the materials and products to be supplied. Part of the materials and products that are used leave the industry together with the goods supplied, either as component or as packaging. The other part of the materials and products is used as final product. After final consumption they leave the industry in the form of waste. This description of material flows inside industries applies to all products that are used. However, for our analysis only the use of *core* materials and products is of importance. In our approach, for each industry the purpose of the input of core materials and products is estimated and divided between packaging, components and final products. This estimate is based on the industry’s supply of goods and general knowledge on packaging practices and

product compositions. Subsequently, packaging and components are allocated to the supply of materials and products of that industry. Finally, the packaging and components are allocated to the users of those materials and products.

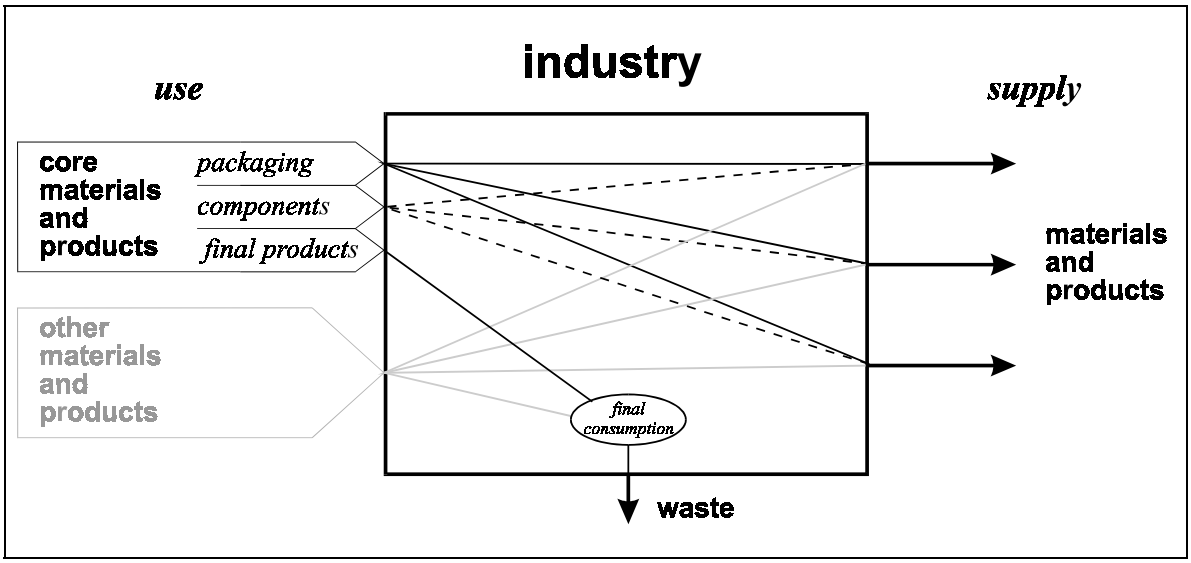

Figure 3 Schematic representation of the allocation of the use of core materials and products by an industry to its supplied goods.

The successive steps of the method, which are described below, are displayed in Figure 4. In this figure a 3-dimensional representation is used, which is explained by the definition block in the upper part of Figure 4. The industries, service sectors and final demand categories are depicted along the x-axis, all goods (all of the goods discerned in the supply and use tables) along the y-axis and the core materials and products along the z-axis. In this space, planes represent tables.

The calculation method for the final consumption of core materials and products consists of the following successive steps:

(1) Evaluation of the purpose of use of core materials and products

To distinguish the different purposes of use, the physical core use table $\mathbf{U_c}$*, containing the use of core materials and products, is split up into several new physical core use tables. The first one is $\mathbf{U_{cp}}$*,* indicating the use of core materials and products to be used as packaging[8]. The second one is $\mathbf{U_{cc}}$*,* indicating the use of core materials and products

[8] Durable packaging which eventually returns to the industry that has bought it and that finally discards it are excluded. The decision whether a use of packaging must be seen as final consumption (table $\mathbf{U_{cf}}$**)** or as intermediate product (table $\mathbf{U_{cp}}$**)** is the consideration whether the packaging is finally discarded by the using industry or by the consumer of the goods produced by that industry.

to be used as component. The third one is $\mathbf{U_{cf}}$***** indicating the use of core materials and products to be used as final product.

Core intermediate materials are processed into core products (see Figure 1), which can be used as packaging, as component or as final product. So in principle it should be sufficient to estimate the purpose of use of core *products* only. However, if the materials processing operation is carried out by the same industry as the packing, assembling or final consuming industry, these core intermediate materials *seem* to be used as packaging, component or final product *directly*, because they appear in the use table only in the form of intermediate materials. In Figure 1 these uses are indicated by dotted lines. In order to make it possible to assign these intermediate materials to the goods they are applied to (as packaging or as component), the purpose of their use (packaging, component or final product) is also evaluated.

If core intermediate materials are used as packaging, component or final product by another industry than the materials processing industry, they appear twice in the core use table: once as intermediate material and once as intermediate or final product (see Figure 1). If both were used in the calculations, this would lead to double counting. In order to avoid this, core intermediate materials to be used for producing core products should be left out of the calculations. In our approach these are collected in a fourth physical core use table, $\mathbf{U_{ci}}$*****, which is not used in further calculations.

The evaluation of the purpose of use can be executed in several ways. The descriptions of some core materials and products in the use table already indicate what purpose they are used for. ‘Plastic packaging’, ‘metal machine parts’ and ‘wooden furniture’ will generally be used for one purpose only, namely as packaging, component and final product respectively. In this case the rows of $\mathbf{U_c}$***** representing the use of those core materials and products can be moved to $\mathbf{U_{cp}}$*****, $\mathbf{U_{cc}}$***** or $\mathbf{U_{cf}}$***** entirely (each using industry uses them for the same purpose). Other core materials and products, however, are used for several purposes. Plastic films for example are either used as packaging, or as component (upholstery), or as final product (agricultural films). For these core materials and products the purpose depends on the user and on the goods he produces. In that case an estimate of the purpose of use of the core material or product per industry is made, based on the industry’s supply of goods and general knowledge on packaging practices and product compositions. As a result, figures from $\mathbf{U_c}$*****, representing the use of those core materials and products by specific industries, are moved individually to $\mathbf{U_{cp}}$*****, $\mathbf{U_{cc}}$***** or $\mathbf{U_{cf}}$*****.

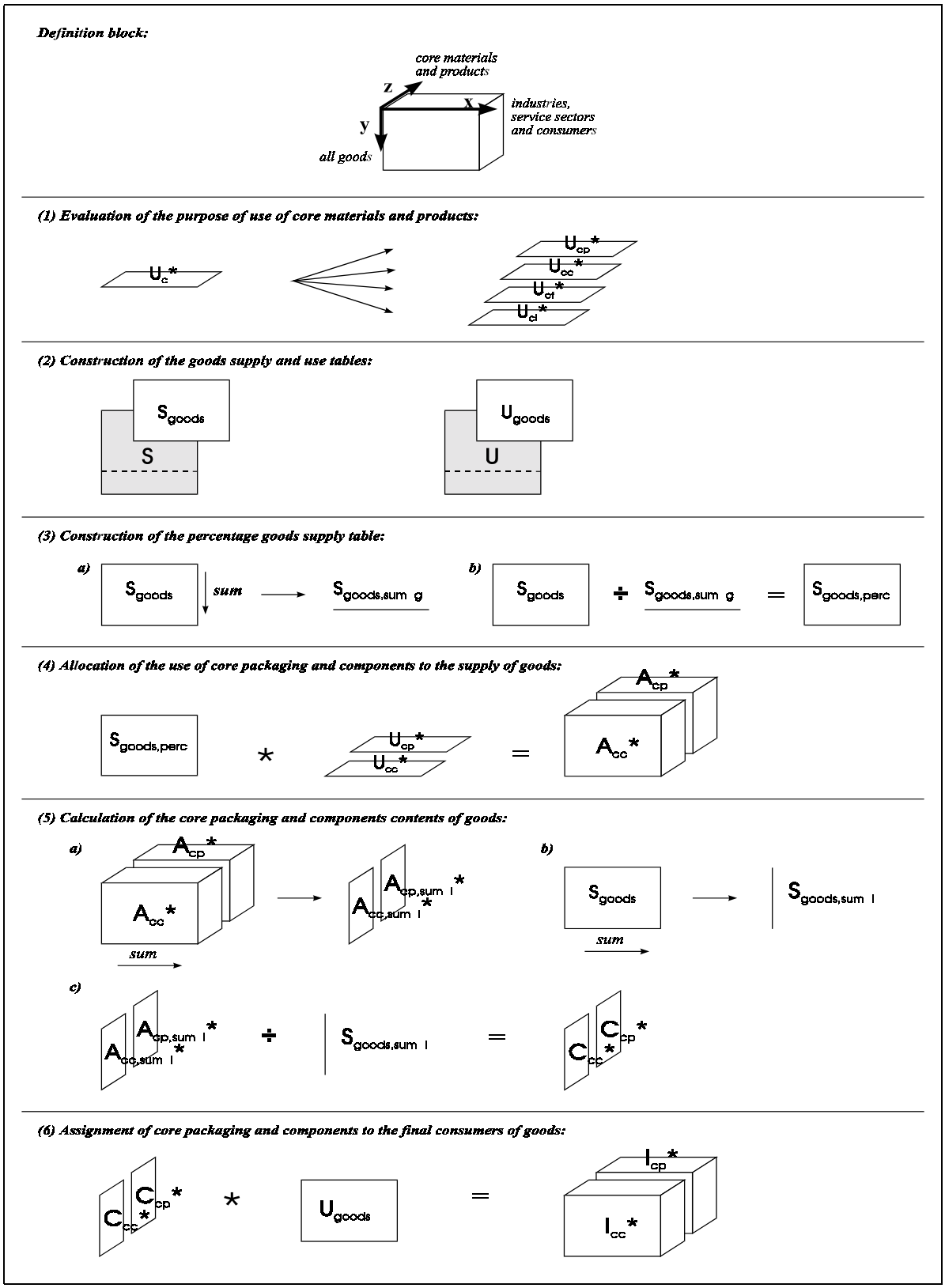

Figure 4 Method to calculate the final consumption of core materials and products. The method consists of 6 successive steps, indicated in this figure. Representation in 3-dimensional space: x-axis: industries, y-axis: all goods, z-axis: core materials and products. An explanation of the abbreviations can be found in the main text.

In the following steps the purchases of packaging and components ($\mathbf{U_{cp}}$* and $\mathbf{U_{cc}}$*) are allocated to the goods they are applied to. For the purchases of core materials and products to be used as final product ($\mathbf{U_{cf}}$*) no further calculation is needed. This table already represents a part of the final consumption: the *direct* final consumption.

(2) Construction of the goods supply and use tables

The original (monetary) supply table contains information on the supply of both goods and services. The supply of services (mainly by service sectors) is not supposed to be accompanied by extensive material flows. Therefore we assume that components and packaging are used for goods, *not* for services. This means that, in the calculations, services do not need to be accounted for. From the original supply table **S** the rows representing products are extracted and services are left out. This results in the goods supply table $\mathbf{S_{goods}}$. For the same reason the original (monetary) use table **U** is reduced to the goods use table $\mathbf{U_{goods}}$.

(3) Construction of the percentage goods supply table

Per industry, all supplies of goods ($\mathbf{S_{goods}}$) are added, forming the total supply of goods per industry ($\mathbf{S_{goods,\ sum\ g}}$). Subsequently, per industry all supplies of goods ($\mathbf{S_{goods}}$) are divided by this total, resulting in the percentage goods supply table $\mathbf{S_{goods,\ perc.}}$ This table represents per industry the percentage, in monetary terms, of the supply of specific goods as part of the total supply of goods by that industry.

(4) Allocation of the use of core packaging and components to the supply of goods

The percentage goods supply table $\mathbf{S_{goods,\ perc}}$ is multiplied by the purchases of core materials and products to be used as packaging $\mathbf{U_{cp}}$* and the purchases of core materials and products to be used as component $\mathbf{U_{cc}}$*. This provides per industry an allocation of core packaging and components to the goods supplied by that industry. It results in two blocks of tables: $\mathbf{A_{cp}}$*, representing the allocation of core materials and products used as packaging and $\mathbf{A_{cc}}$*, representing the allocation of core materials and products used as component.

(5) Calculation of the core packaging and components contents of goods

$\mathbf{A_{cp}}$* and $\mathbf{A_{cc}}$* show for each industry the assignment of purchased core materials and products to the commodities supplied. The sum per commodity of $\mathbf{A_{cp}}$* and $\mathbf{A_{cc}}$* represents the assignment of the total purchased core materials and products, used as packaging or as component, to each supplied commodity ($\mathbf{A_{cp,\ sum\ i}}$* and $\mathbf{A_{cc,\ sum\ i}}$*; see Figure 4). The core packaging and components contents of goods are calculated by dividing the sum per commodity of $\mathbf{A_{cp}}$* and $\mathbf{A_{cc}}$* by the total national supply of commodities $\mathbf{S_{goods,\ sum\ i}}$. Two tables result: $\mathbf{C_{cp}}$* showing the core materials and products

contents, used as packaging, of all goods; $\mathbf{C_{cc}}$***** showing the core materials and products contents, used as component, of all goods[9].

(6) Assignment of core packaging and components to the final consumers

Purchases of goods are found in the goods use table $\mathbf{U_{goods}}$. Core materials and products, used as packaging or as component, are assigned to the final consumers by multiplying $\mathbf{U_{goods}}$ by the core materials and products contents $\mathbf{C_{cp}}$***** and $\mathbf{C_{cc}}$***** obtained in step (5). Value added in trade and transportation has to be taken into account[10]. The assignment results in two blocks of tables, $\mathbf{I_{cp}}$***** and $\mathbf{I_{cc}}$*****, representing the *indirect final consumption*, showing *which core materials and products* are used, as packaging and as component respectively, *connected to which goods, by which final consumers* (see Figure 4).

One of the users discerned in the use table is 'exports'. This means that in our method exported products are ascribed core packaging and component contents too (called *indirect exports*). Also *imported* products have core packaging and components contents. 'Imports' is one of the 'suppliers' in the supply table. As a first order approach we assume that imported goods have a similar composition and are packed the same way as goods that are produced in domestic industry. *Indirect* imports are calculated by applying the core materials and products contents $\mathbf{C_{cp}}$***** and $\mathbf{C_{cc}}$***** to the imports figures from the supply table **S**.

In order to present the results, the indirect final consumption tables $\mathbf{I_{cp}}$***** and $\mathbf{I_{cc}}$***** are summed and aggregated. Summation in the x- and y-direction leads to a pair of vectors that show the total national indirect final consumption of the core materials and products in the form of packaging and components respectively. By summation in the y- and z-direction a pair of vectors is obtained that show the indirect final consumption of core materials and products used as component and packaging, divided between the final consumers. Finally, summation in the x- and z-direction leads to a pair of vectors that show the final consumption of core materials and products used as component and packaging, divided between the goods they are applied to.

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[9] An example of what can be read from the different tables: $\mathbf{A_{cp}}$*****: x [kg] of plastic films are used *by the food processing industry* as packaging for potatoes. $\mathbf{A_{cp,\ sum\ i}}$*****: X [kg] of plastic films are used *by the total national industry* as packaging for potatoes. $\mathbf{S_{goods,\ sum\ i}}$: the total national supply of potatoes amounts to Y [$]. Then $\mathbf{C_{cp}}$*****: the plastic film content, used as packaging, of potatoes equals X/Y [kg/$].

[10] Because of value added in trade and transportation, purchase prices are not equal to supply prices. Therefore core materials and products contents (expressed in [kg/$]) are not equal for purchases and supplies. Using the value added, core materials and products contents for supplies are converted into core materials and products contents for purchases.

2.3 *Discussion*

In this section the reliability of the STREAMS method is discussed. In paragraph 2.3.1 we discuss a number of considerations about the use of supply and use tables as data sources for the analysis of material flows. In paragraph 2.3.2 we discuss the method to calculate the final consumption. In paragraph 2.3.3 the accuracy of the results is discussed and some remarks are made based on preliminary results of case studies, which are presently being conducted using the STREAMS method.

2.3.1 Using supply and use tables for material flows research

One of the reasons for developing the STREAMS method was to avoid the disadvantages of collecting data from different data sources, *i.e.* dissimilarities in definitions, in subdivisions of product groups and in reference years. Because in the STREAMS method nearly all input data is extracted from the country's supply and use tables, no dissimilarities are to be expected. However, the use of supply and use tables for the analysis of material flows involves some problems to be solved.

The lowest possible aggregation level that can be achieved in the analysis is determined by the level of aggregation of the data in the supply and use tables. The subdivision of industries and commodities that is used in the supply and use tables must also be used in the STREAMS method and affects the presentation of the results on low aggregation levels. So the possibility of deriving useful results highly depends on the aggregation level of the supply and use tables. If the aggregation level of the supply and use tables is too high, core materials and products become part of wide groups of goods, making it impossible to derive results on the core materials or products separately. Since the aggregation level of the supply and use tables differs considerably between countries, the usefulness of these tables as data sources for the analysis of material flows differs between countries as well.

In common supply and use tables *industries* are discerned, not *activities* or *processes*. Most industries discerned in statistics consist of a mixture of activities, although they are categorised in statistics according to their *main* activity. The mixture may partly be due to the aggregation level of the statistical data: if the aggregation level is high, companies with rather different main activities are categorised in the same industry, making it impossible to determine for which activity a specific commodity is bought by a specific industry. In some countries, statistical offices recognise this problem and try to construct *functional* or *homogeneous* supply and use tables, in which activities are discerned instead of industries. For The Netherlands this has been done by Statistics Netherlands (Konijn *et al.*, 1993). However, for most countries, these tables are not available on sufficiently low aggregation levels.

In the supply and use tables, waste figures only concern commercial waste flows that are traded. Since the greater part of the waste flows, like household waste, is not traded, it is not possible to derive data on them from the supply and use tables. For this stage of the analysis other data sources or estimates are necessary.

The conversion of monetary data into physical data is a critical step in the STREAMS method. The accuracy of the method largely depends on the way this step is conducted. Statistics Netherlands has made an effort to construct physical supply and use tables for The Netherlands for some material flows (Konijn *et al.*, 1995). For the analysis of material flows this type of tables would be very useful. However, because a lot of work is involved in constructing these tables, it is very unlikely that they will become available for many materials and products, for many years and for many countries[11].

2.3.2 Calculating the final consumption

In the successive steps of the STREAMS method to calculate the final consumption of core materials and products, a number of assumptions and estimates is made that influences the accuracy of the results. The main aspects are discussed in this paragraph.

In the first step of the final consumption analysis, an estimate is made of the purpose of use of core materials and products by industries. This estimate is mainly based on considerations about the purchasing industries and the goods they produce, combined with general knowledge on packaging methods and product compositions. More detailed studies of industries and their products are needed to achieve more accurate estimates.

The supply and use tables contain both goods and services. We assume that the supply of services is not accompanied by transfer of materials, although in practice services involve relatively small transfers of *e.g.* spare parts and printed paper. As a result, all use of core materials and products by service industries, including trade, is regarded as final consumption.

It is impossible to assign packaging and components used in trade to the goods they are applied to, because the supply and use tables do not indicate whether goods are bought from trade or directly from the producing industry. This leads to overestimating the direct final consumption of core materials and products by trade.

[11] Statistics Netherlands convert monetary supply and use tables into physical tables using specific prices for each industry, combined with balancing principles. Hekkert *et al* (2000) propose to include this method into the STREAMS method.

In our method, packaging and components purchased by an industry are allocated to all goods supplied by that industry, *on a monetary basis*. In other words: the supply of each industry is assumed to consist of a range of similar goods with respect to composition, packaging method and retail price. Therefore, supply and use tables with lower aggregation levels, and consequently more homogeneous industries, lead to more accurate results. The fact that packaging and components that are purchased by an industry are allocated to *all* products supplied by that industry may, on a detailed level, lead to some strange results, *e.g.* living pigs getting a plastic package content because of use of plastic packaging in agriculture. It is possible to refine the calculation method by adding another step, not only estimating whether the purchased core materials and products are used as final product, as packaging, or as component, but also estimating which goods they are applied to[12]. However, this leads to much extra research effort as well as the need for a more detailed knowledge about the way of packing and the composition of all of the goods discerned in the use- and supply-tables.

Imported goods are assumed to be comparable to domestically produced goods, with regard to prices, composition and packaging method. This may cause inaccurate results for goods that are imported but not produced in the country under investigation. Because no core materials and products are used as packaging or as component for those goods in the investigated country, no core materials and products are assigned to the imported goods either. This means that the core materials and products coming along with those imported goods are neglected. Figures are more accurate for goods for which imports play a minor role. For exported goods a similar assumption is made: prices, composition and packaging method are assumed to be the same for exported goods as for goods on the domestic market.

2.3.3 Accuracy of the results

The STREAMS method has been tested in case studies on the plastics flows (see Chapter 3) and on the paper and wood flows (Hekkert *et al.*, 2000) in The Netherlands for the year 1990. The most extensive supply and use tables published by Statistics Netherlands (CBS, 1993) contain the supply and use of 529 commodities and 114 services by 123 industries, 104 service sectors and 10 final demand categories (see Figure 2). Among the commodities that are discerned, there are 17 plastic materials and products, 37 paper materials and products and 26 wood materials and products. This suggests that the supply and use tables are reasonably detailed to be useful for the analysis of the plastics, paper and wood flows in The Netherlands.

The results of the analyses indicate that application of the STREAMS method provides detailed insight into the flows of the materials under investigation through the economic system of The Netherlands. Especially the *indirect* final consumption of materials, used as

[12] In (Hekkert *et al.*, 2000) the feasibility of including this step in the STREAMS method is assessed.

packaging or as component, can be studied in detail[13]. However, it is rather difficult to compare the results of the STREAMS method to the results of other studies, because detailed studies on the *final* consumption of products and materials are lacking almost completely and because estimates on final consumption often use different definitions, subdivisions of product groups and reference years, whereas the reliability of these estimates is often questionable.

The input data of the STREAMS method, data from the supply and use tables, is fairly accurate. In countries like The Netherlands and Germany, these tables are constructed by the national statistical offices, based on data collected from extensive surveys. However, in the subsequent calculation steps of the STREAMS method inaccuracies are introduced. Because most of the inaccuracies concern uncertainties in modelling the real world, for which assumptions have to be made of which the extent of correctness is unknown, it is rather difficult to estimate the inaccuracy of the results.

Nevertheless, we estimate that, on disaggregated levels, the mean deviation of the results is about 30% (see Chapter 3). Hekkert *et al.* (2000) propose several improvements to the method, which reduce the mean deviation on disaggregated levels to about 15%. In general it is expected that the accuracy increases if the results are presented on a higher aggregation level. *E.g.*, assigning core materials and products to individual commodities produced by an industry may lead to large inaccuracies when assessing the individual commodities. However, on a more aggregated level, the individual goods fall into a single group of commodities. This means that figures for the complete group are more accurate than figures for individual commodities.

2.4 Conclusions

Several countries publish annual supply and use tables to present a detailed description of their economy. As these tables show the supply and use of materials and products by industries and consumers, they contain a lot of information on the material flows through the country's economy. A condition for them being useful for the analysis of material flows is that they are sufficiently detailed. Supply and use tables differ considerably in size between countries, so their usefulness differs between countries.

In this article a new method, called the STREAMS method, is proposed to analyse material flows through society, using these national supply and use tables. Since common supply and use tables consist of monetary data, they cannot be used directly for material flows research.

[13] 17 plastic products, 37 paper products and 26 wood products assigned as packaging or component to 529 commodities, which are consumed by 228 consumers.

First they have to be converted into physical units. The applied conversion method affects the accuracy of the results.

The STREAMS method is not limited to the direct supply and use of core materials and products. It can also be used to calculate the final core materials consumption of industrial sectors and households, *i.e.* the place where the core materials and products are finally consumed and turned into waste. The method to calculate the final consumption of core materials and products consists of several steps, some of which are based on assumptions on modelling material flows in society. The correctness of these assumptions, and hence the extent of congruency between the model and reality, determines the accuracy of the results of the method. There are two critical steps. Firstly, the estimate whether core materials and products are used by industries as packaging, as component or as final product. Secondly, the allocation of the packaging and components used by industries to the goods supplied by those industries. Both steps can be improved using more extensive studies, resulting in more accurate results but also leading to more research effort.

If, furthermore, data on waste release and recycling is added, the scheme of core material flows through society can be completed and the flow of core materials can be followed 'from cradle to grave'.

Case studies on the flows of plastics, paper and wood through The Netherlands have shown that the STREAMS method can serve as a powerful tool to obtain detailed knowledge about material flows through society. It provides data on the final consumption of products, which cannot be obtained from other studies and for which, up to now, only relatively rough estimates were available. Although comparison of the results of the STREAMS method to results of other studies is very difficult and often impossible, the case study on plastic flows in The Netherlands suggests that the results are, at least on aggregated levels, reasonably accurate. The case study on paper and wood flows in The Netherlands shows that the accuracy of the results can be further increased by including a number of improvements to the calculation method. In order to test the wider applicability of the method, further research should aim at applying it to the analyses of different material flows through different countries for which supply and use tables are available.

2.5 References

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Chapter 3

Assessment of the plastic flows in The Netherlands using STREAMS[1]

Abstract

The STREAMS method, a method for material flow analysis based on national supply and use tables, is examined in an assessment of the flows of plastics in The Netherlands, for the reference year 1990. The method proves to be a powerful tool to get a total overview of plastic flows in The Netherlands. Using the method, it is possible to obtain a highly detailed view on the final consumption of materials, for which hitherto only highly aggregated estimates were available. With the STREAMS method, total final plastics consumption in The Netherlands in the year 1990 is calculated at 1260 ktonnes, which fairly matches other estimates in literature. The STREAMS method also provides information on the final consumption of plastics on lower aggregation levels, *e.g.* the final consumption of plastics divided between industry sectors, split up between packaging, components and final products. Our calculations show that with regard to plastics in The Netherlands, apparent consumption, calculated as raw materials production plus imports minus exports, although easily calculable, is a rather poor approximation for final consumption. Several issues that affect the accuracy of the results of the STREAMS method are discussed and estimates are made of their contributions to the mean deviation of the results. Total mean deviation is calculated at ± 30% for results presented on lower aggregation levels. On higher aggregation levels the accuracy of the results is much higher.

[1] Published as: Joosten, L.A.J., Hekkert, M.P., Worrell, E., *Assessment of plastic flows in The Netherlands using STREAMS*, Resources, Conservation and Recycling 30 (2), 2000, pp. 135-161.

3.1 Introduction

Material Flow Analysis is a tool for getting insights in the volumes and characteristics of material flows through the economy. To reach a more sustainable materials consumption pattern a good understanding of current material flows is a prerequisite.

In The Netherlands several institutes and organisations regularly publish information about material flows through the economy. Statistics Netherlands (CBS) publishes data on materials used by various industries, as well as data on foreign trade. Waste flows are analysed by the National Institute of Public Health and Environmental Protection (RIVM). Branch organisations provide information on several more specific material flows. With regard to plastics the Dutch Federation for Plastics (NFK) and the Association of Plastics Manufacturers in Europe (APME) publish data. Apart from these, various figures for specific flows are mentioned in other publications. However, in these publications a lot of different definitions, subdivisions and reference years are used, making it very difficult to combine data from different studies to obtain a complete picture of material flows through the economy.

Another problem is that, in literature, data on the *final consumption* of materials and products is very hard to be found. In general only direct[2] supplies and purchases are mapped. However, goods that are purchased by industries are either used as final product, or as packaging, or as component. In the latter two cases the purchasing industry is not the final consumer. Packaging and components become part of the products of the industry. Together with these products the packaging and components reach the final consumer of those products. *He* is considered as the final consumer of the packaging and components as well.

In Chapter 2 we described the STREAMS method we developed to map material flows through society, based on the country's supply and use tables. As the STREAMS method only uses the country's supply and use tables as data source, no dissimilarities in definitions, subdivisions and reference years are to be expected. Depending on the level of detail of the supply and use tables, the results of the method can be highly detailed. Using the STREAMS method it is possible to assess material flows through society 'from cradle to grave'. It includes a calculation method for the stage of *final consumption*, in which all goods, including packaging and components, are assigned to the final consumer.

[2] In our terminology 'direct' uses refer to uses of materials and products that can be read directly form statistics: one industry or consumer buys certain goods from another. Indirectly used are the materials embodied in product flows, *e.g* packaging materials and components that come together with those goods.

In this article the STREAMS method is tested in a case study on the plastic flows through The Netherlands in the year 1990. The objective is to obtain detailed and complete information on the volumes of plastic flows through all stages, from cradle to grave. First, in section 3.2, an outline of the STREAMS method is given. Subsequently, the application of the method to the plastic flows in The Netherlands is described stepwise in section 3.3. The applicability of the method, the results and their reliability are discussed in section 3.4. Finally, in section 3.5, conclusions are drawn.

3.2 The STREAMS method

In this section the STREAMS method is summarised. For a comprehensive description we refer to Chapter 2.

The STREAMS method consists of two parts: the supply and use analysis and the final consumption analysis. In the supply and use analysis data on the direct supply and use of the materials under investigation is subtracted from the supply and use tables. In the final consumption analysis this data is used to calculate the final consumption of materials and products. It focuses on packaging and components, which are followed from the industries that use them to the final consumers of the products they are applied to.

The *supply and use analysis* contains the following steps:

First a *process scheme* of the material under investigation is constructed and core materials, core products and core industries are assigned. Those are the materials, products and industries that play a mayor role within the materials system under investigation. From the supply and use tables the rows concerning core materials and core products are selected, from which a *core supply table* and a *core use table* are obtained. These monetary tables are corrected for confidential trade, converted into physical units and corrected for intrasectoral trade. Finally, the core materials content of core products is calculated.

If the core supply and use tables are sufficiently detailed, it is possible to read from them the direct use and supply of core raw materials, core intermediate materials, core products and core waste materials. These data are used in the *final consumption analysis* to calculate the final consumption of core materials and products.

The *final consumption analysis* contains the following steps:

All uses of goods from the core supply and use tables by industries are evaluated and the purpose of use is estimated. By this procedure a division is made between uses as final product, as component and as packaging. Subsequently, each industry’s uses of packaging

and components are allocated to the products of that industry. This way the products get packaging and components contents. Finally, these packaging and components are allocated to the users of the products in question.

3.3 Application of the STREAMS method to plastic flows in The Netherlands

In this section the STREAMS method is applied to the flows of plastics in The Netherlands in 1990. The calculations start from the supply and use tables provided by Statistics Netherlands (CBS, 1993)[3]. These tables are composed as shown in Figure 1. Together they present a total description of The Netherlands' economy in terms of the supply and use of 529 goods and 114 services by 123 industries, 104 service sectors and 10 'final demand categories'[4], as well as imports and exports. All figures are expressed in monetary units and concern the year 1990.

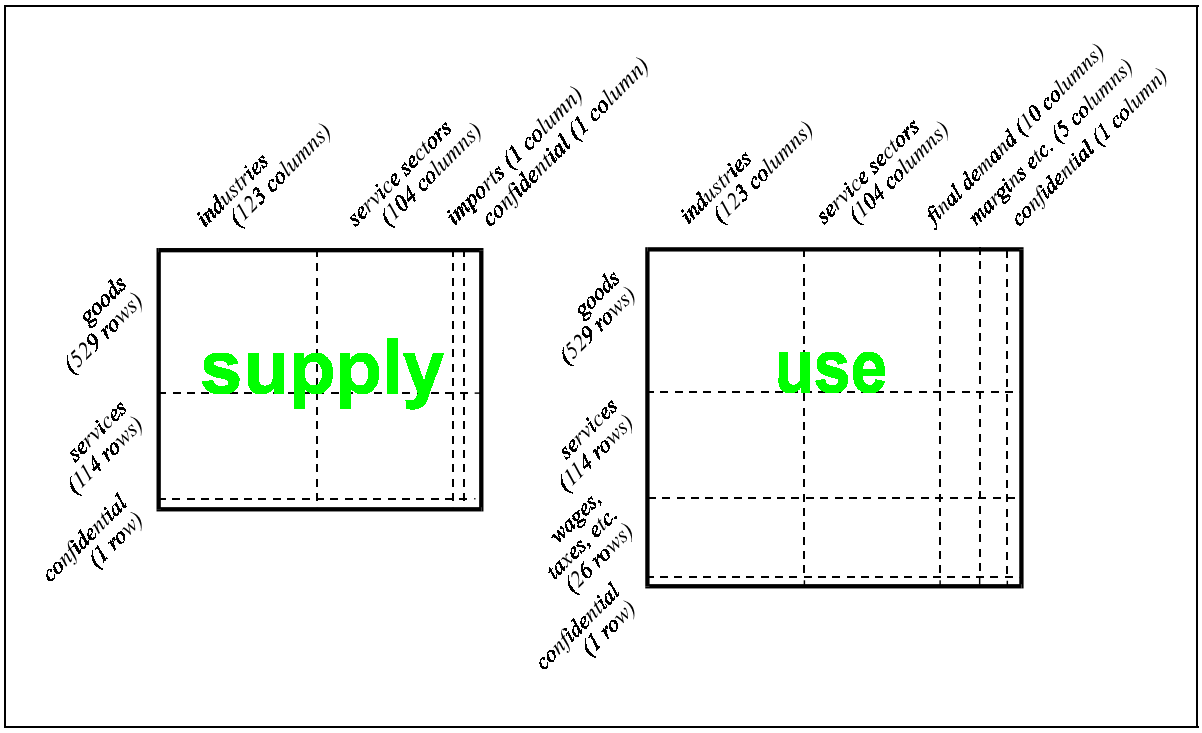

Figure 1 Supply and use tables of The Netherlands

[3] In the publication indicated, tables were aggregated in order to get a surveyable presentation. However, in our calculations the original non-aggregated tables were used.

[4] households, government, exports, investments, stock increase

3.3.1 The supply and use analysis

In the supply and use analysis the direct use and supply of plastic materials and products is assessed.

Stepwise description of the supply and use analysis

In this paragraph the application of the supply and use analysis to the flows of plastics in The Netherlands in 1990 is described stepwise.

(1) Construction of the process scheme of plastics and assignment of core materials, core products and core industries.
The process scheme of plastics is shown in Figure 2. Materials enter the scheme as feedstocks, which are processed into primary plastics, mostly in the form of granulates. Primary plastics are processed into plastic products, part of which are final products that are ready for final consumption. Plastic packaging and components, however, need a packing and assembling operation respectively before reaching the final consumer. After some time of use, plastic products are discarded as post consumer plastic waste. Part of the post consumer plastic waste is recycled and used as secondary raw material (feedstock recycling)[5] or secondary intermediate material (mechanical recycling). Also a part of the production, processing, packaging and assembly wastes, arising in the various processing steps, is recycled. The remainder of the plastic wastes, called final plastic wastes, is incinerated or landfilled.

For the investigation of plastic flows, the supply and use tables of The Netherlands contain data on a number of relevant materials and products, which we call *core* materials and products. They are listed in Table 1. One row in the supply and use tables concerns 'primary plastics', which represents all plastic intermediate materials (see Figure 2). Furthermore, fifteen plastic products are discerned. Finally, there is one row representing plastic wastes.

Plastics are produced from fossil feedstocks. Although these feedstocks are discerned in the supply and use tables, it is impossible to make out which part is used for plastics production, because they are used to produce a whole range of commodities, of which plastics only form a part. Waste figures in the supply and use tables only concern wastes that are traded. Because the major part of post consumer plastic waste is not traded, figures from the supply and use tables about plastic wastes are incomplete and therefore unusable for the analysis.

[5] In the reference-year 1990, this process was not yet used in The Netherlands

Table 1 Plastic materials and products discerned in the Netherlands supply and use tables.

Primary plastics	
Plastic products:	
	Plastic building materials[a]
	Plastic industrial components
	Plastic films and sheets, cellular
	Plastic films and sheets, reinforced
	Plastic films and sheets, others
	Plastic tubes
	Plastic rods and profiles
	Plastic floor covering
	Plastic furniture
	Plastic lighting
	Plastic packaging[b,c]
	Refuse bags
	Adhesive tape
	Plastic office and school supplies
	Other plastic products[d]
Plastic wastes	

[a]Excluding plastic products of the other product categories used in building; [b]including durable plastic packaging, like pallets, crates and containers; [c]excluding plastic products of the other product categories used as packaging material; [d]Plastic footwear and clothing, brushes, combs, tailor's dummies *etc.*;

In the supply and use tables, the producers of primary plastics fall into the categories 'industry of synthetic resins' and 'other chemical industries'. Primary plastics are largely processed into plastic products by the 'plastics processing industry'. But also other industries use primary plastics. Firstly, there are some industries of which the processing of primary plastics into plastic products forms only a minor activity. Secondly, primary plastics are used to produce *non-plastic products* like synthetic fibres, coatings, glues, etc., which are not rated among the plastic products. Non-plastic products are not considered in this analysis.

As can be seen from Figure 2, direct information from the supply and use tables mainly concerns the 'intermediate materials' and 'intermediate products' stages.

(2) Construction of the plastics supply and use tables

In the second step the rows representing the uses of primary plastics and plastic products are selected from the use table and ordered to form the plastics use table. This table shows the uses of primary plastics and plastic products by individual industries, service sectors and final demand categories, expressed in monetary units. Similarly, a plastics supply table is composed out of the supply table, representing the supplies of primary plastics and plastic products. In Table 2 the aggregated supplies and uses of primary plastics and plastic products by the main industries, as derived from the plastic supply and use tables, are presented[6,7].

[6] 1 Dfl ≈ 0.55 US$ ≈ 0.43 ECU (1990)

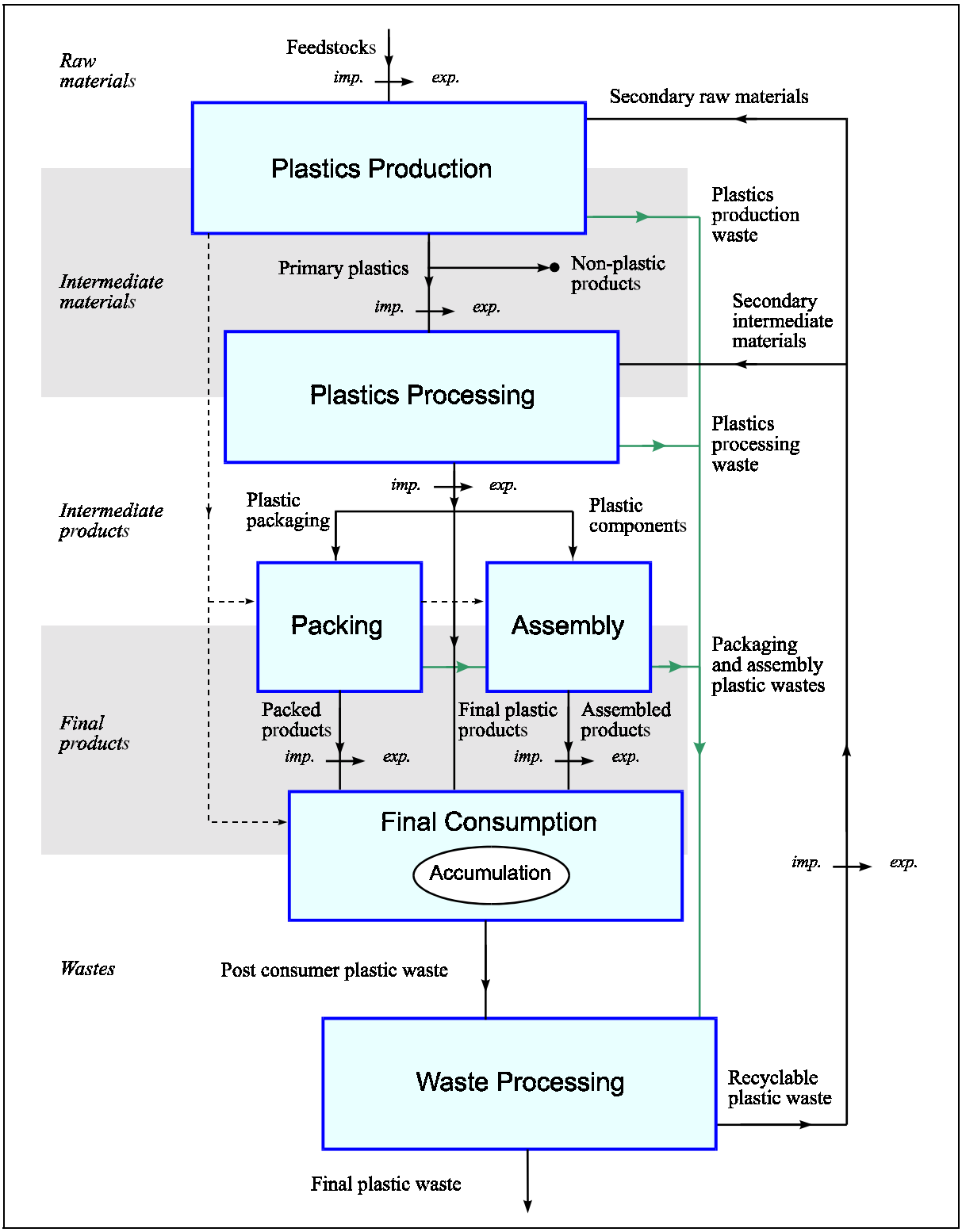

Figure 2 Scheme of plastic flows through the economy

[7] The tables in this report were aggregated in order to obtain a surveyable output. For the calculations, however, the original, full dimension tables are used.

Table 2 Supply and use of primary plastics and plastic products in 1990, as read from The Netherlands' supply and use tables

	Primary plastics		**Plastic products**[a]	
	Supply [mil. Dfl.]	**Use** [mil. Dfl.]	**Supply** [mil. Dfl.]	**Use** [mil. Dfl.]
Industry of synthetic resins	0	333	0	67
Other chemical industries	5961	204	9	205
Plastics processing industry	106	2346	5955	895
Other industries, service sectors and consumers	61	1451	508	9837
Confidential	3774	0	2301	0
Margins[b]	-	-786	-	-1891
Imports / exports	3820	10174	6064	5724
Total	**13722**	**13722**	**14837**	**14837**

[a]aggregated; [b]trade and transportation margins and product related taxes and subsidies

(3) Correction for confidential supplies

From Table 2 it is obvious that a considerable part of the supplies of primary plastics and plastic products is confidential. In the supply table confidential supplies are collected in a column 'confidential', which shows per product the amount of confidential supplies by the total Netherlands industry. There is also a row showing the total amount of confidential supplies per industry (see Figure 1).

Table 2 shows that, in the year 1990, 3774 million Dfl. of *primary plastics* supplies were confidential. On the other hand, according to the supply table, the total confidential supplies of the industry of synthetic resins amounted to 4198 million Dfl. The supply table shows no supply of primary plastics by the industry of synthetic resins (Table 2), whereas in fact primary plastics are the characteristic products of this industry. Therefore we assume that the confidential primary plastics supplies were in fact supplies by the industry of synthetic resins.

In 1990, the confidential supply of *plastic products* amounted to 2301 million Dfl (Table 2), whereas the confidential products supplies by the plastics processing industry amounted to 1818 million Dfl (supply table). We assume that the latter entirely consist of plastic products. Therefore 80% (1818/2301) of the confidential supplies of plastic products was added to the supply of the plastics processing industry.

As can be seen from Table 2, confidential *uses* of plastic materials and products play no role. The aggregated results of the correction are shown in Table 3.

Table 3 Supply and use of primary plastics and plastic products in The Netherlands in 1990, corrected for confidential trade

	Primary plastics		**Plastic products**	
	Supply [mil. Dfl.]	**Use** [mil. Dfl.]	**Supply** [mil. Dfl.]	**Use** [mil. Dfl.]
Industry of synthetic resins	3774	333	0	67
Other chemical industries	5961	204	9	205
Plastics processing industry	106	2346	7773	895
Other industries, service sectors and consumers	61	1451	508	9837
Confidential	0	0	483	0
Margins	-	-786	-	-1891
Imports / exports	3820	10174	6064	5724
Total	**13722**	**13722**	**14837**	**14837**

(4) Conversion of the monetary plastics supply and use tables into their physical equivalents

For the analysis of material flows data expressed in physical units is needed. Therefore the plastics supply and use tables have to be converted from monetary units into physical units. In this analysis this is done relatively roughly, using a mean price for each plastic material or product, regardless of the using industry. Mean prices are calculated on the basis of the CBS statistics of foreign trade (CBS, 1992a). These statistics are expressed in physical as well as in monetary units, making it possible to calculate mean export prices. We assume that mean prices on the domestic market do not differ considerably from mean export prices. Therefore we use exports prices for both international and domestic transactions. Physical plastics supply and use tables are obtained by dividing the monetary plastics supply and use tables by the mean exports prices for the various plastic materials and products[8]. The conversion is shown in Table 4, whereas Table 5 shows the aggregated results of this step.

[8] Due to trade and transportation margins, taxes and subsidies (collected in the column 'margins'), supply prices differ from use prices (like exports). This difference is taken into account by using a correction factor to the supply prices, calculated as the quotient of the total use including and excluding margins.

Table 4 Supply and use of primary plastics and plastic products in The Netherlands in 1990; Conversion from monetary units into physical units

	Supply [mil. Dfl.]	**Price** [Dfl./kg.]	**Supply** [ktonne]	**Use** [mil. Dfl.]	**Price** [Dfl./kg.]	**Use** [ktonne]
Primary plastics	**9902**	**2.65**	**3733**	**4334**	**2.80**	**1546**
Plastic products:						
Plastic building materials	851	12.85	66	914	14.86	62
Plastic industrial components	613	16.39	37	810	17.46	46
Plastic films and sheets, cellular	319	7.99	40	260	8.49	31
Plastic films and sheets, reinforced	165	7.11	23	199	7.84	25
Plastic films and sheets, others	1347	5.52	244	1649	5.91	279
Plastic tubes	822	6.75	122	862	7.47	115
Plastic rods and profiles	360	7.80	46	373	8.43	44
Plastic floor covering[a]	267	4.46	60	308	5.78	53
Plastic furniture	277	6.49	43	271	7.49	36
Plastic lighting	14	18.47	1	89	22.52	4
Plastic packaging	1932	5.78	334	2601	6.41	406
Refuse bags	81	3.43	24	135	5.72	24
Adhesive tape	109	7.91	14	187	9.86	19
Plastic office and school supplies	147	10.05	15	231	12.00	19
Other plastic products	1469	8.66	170	2115	10.20	207
Plastic products, total	**8773**		**1238**	**11004**		**1371**

[a]Mean use price: 13.01 [Dfl/m^2]; converted into [Dfl/kg] using the average weight of polyamide consumer carpets = 2.25 [kg/m^2] which comprise the majority of this product category (Potting *et al*, 1993).

Table 5 Supply and use of primary plastics and plastic products in The Netherlands in 1990, corrected for confidential trade and converted into physical units

	Primary plastics		**Plastic products**	
	Supply [ktonne]	**Use** [ktonne]	**Supply** [ktonne]	**Use** [ktonne]
Industry of synthetic resins	1423	119	0	11
Other chemical industries	2247	73	1	30
Plastics processing industry	40	837	1098	127
Other industries, service sectors and consumers	23	517	59	1203
Confidential	0	0	80	0
Imports / exports	1440	3628	871	738
Total	**5174**	**5174**	**2108**	**2108**

(5) Correction for intrasectoral trade

From Table 5 it can be concluded that intrasectoral trade plays a role: industries sell certain amounts of their input materials and buy certain amounts of their output products. Further calculations call for a correction of this fact. In our approach mutual trade within industries is corrected for by calculating per industry the net use of input materials and the net supply of output products. The aggregated results of this correction are shown in Table 6.

Table 6 Supply and use of primary plastics and plastic products in The Netherlands in 1990, corrected for confidential trade and intrasectoral trade

	Primary plastics		**Plastic products**	
	supply [ktonne]	**Use** [ktonne]	**supply** [ktonne]	**use** [ktonne]
Industry of synthetic resins	1304	0	0	11
Other chemical industries	2175	0	1	30
Plastics processing industry	0	797	972	0
Other industries, service sectors and consumers	23	517	59	1203
Confidential	0	0	80	0
Imports / exports	1440	3628	871	738
Total	**4942**	**4942**	**1982**	**1982**

(6) Calculation of the primary plastics content of plastic products

With the data from Table 6 a material balance analysis of the plastics processing industry is made. Table 6 shows that the plastics processing industry used 797 ktonnes of primary plastics, whereas the total supply of plastic products by this industry amounted to 972 ktonnes. Comparing the outputs with the inputs, and taking into account 42 ktonnes of plastic waste arising from this industry (as discussed later in this paragraph), it becomes clear that plastic products do not entirely consist of primary plastics. In fact they contain all kinds of additives. Furthermore, products like plastic lighting are composed of several parts, some of which are not made of plastics. Also, plastic products may contain secondary (recycled) plastics, which are not included in the 797 ktonnes of primary plastics used. The material balance shows that on average 78% of plastic products consists of primary plastics. Therefore all figures in the physical plastic supply and use tables concerning plastic products were multiplied by this percentage in order to calculate the amount of primary plastics incorporated. Consequently, henceforward all figures concerning plastic products refer to their primary plastics content. Table 7 shows the aggregated results of the conversion into primary plastics content.

Plastic wastes

Two types of plastic wastes are discerned: firstly post consumer plastic waste, consisting of the waste from final consumption and secondly industrial plastic waste, consisting of material losses from the production, processing and assembly of plastics and plastic products, as well as plastic packaging waste arising from packing products.

As the data on plastic wastes in the supply and use tables are incomplete and therefore not usable for the analysis, also other data sources are explored. According to the APME (1992) post consumer plastic wastes in The Netherlands in 1990 amounted to 781 ktonnes. 87 ktonnes of these were mechanically recycled, 265 ktonnes were incinerated and 429 ktonnes were disposed of by landfilling. From an inquiry into industrial wastes by Statistics

Netherlands (CBS, 1992b), it is concluded that plastic production wastes in the chemical industry in 1990 amounted to 40 ktonnes, whereas the total plastic wastes from plastics processing amounted to 83 ktonnes. An overview of The Netherlands' plastic wastes is presented in Table 8.

Table 7 Supply and use of primary plastics and plastic products in The Netherlands in 1990, corrected for confidential trade, intrasectoral trade and primary plastics content

	Primary plastics		**Plastic products**	
	Supply [ktonne]	**Use** [ktonne]	**Supply** [ktonne]	**Use** [ktonne]
Industry of synthetic resins	1304	0	0	8
Other chemical industries	2175	0	1	23
Plastics processing industry	0	797	755	0
Other industries, service sectors and consumers	23	517	46	934
Confidential	0	0	62	0
Imports / exports	1440	3628	676	573
Total	**4942**	**4942**	**1539**	**1539**

Table 8 Plastic wastes and mechanical recycling in The Netherlands in 1990

	Total [ktonne]	**Mechanical recycling**[d] [ktonne]
Post consumer waste[a]	**781**	**87**
Production and processing wastes[b]:		
Chemical industry	40	15
Plastics processing industry	42	31
Other industries[c]	41	23
Production and processing wastes, total	**123**	**69**
Total	**904**	**156**

[a](CBS, 1992b); [b](APME, 1992); [c]Industrial plastic waste from producing plastic products by 'other industries' plus plastic packaging and assembly waste; [d]Including internal recycling

Results of the supply and use analysis

The calculations described above result in detailed physical plastic supply and use tables, in which the direct supply and use of primary plastics and 15 plastic products by 237 industries, service sectors and consumers is described. Using these tables the material flows in the first stages of the life-cycle (the upper part of Figure 2) can be quantified. The results are shown in Figure 3.

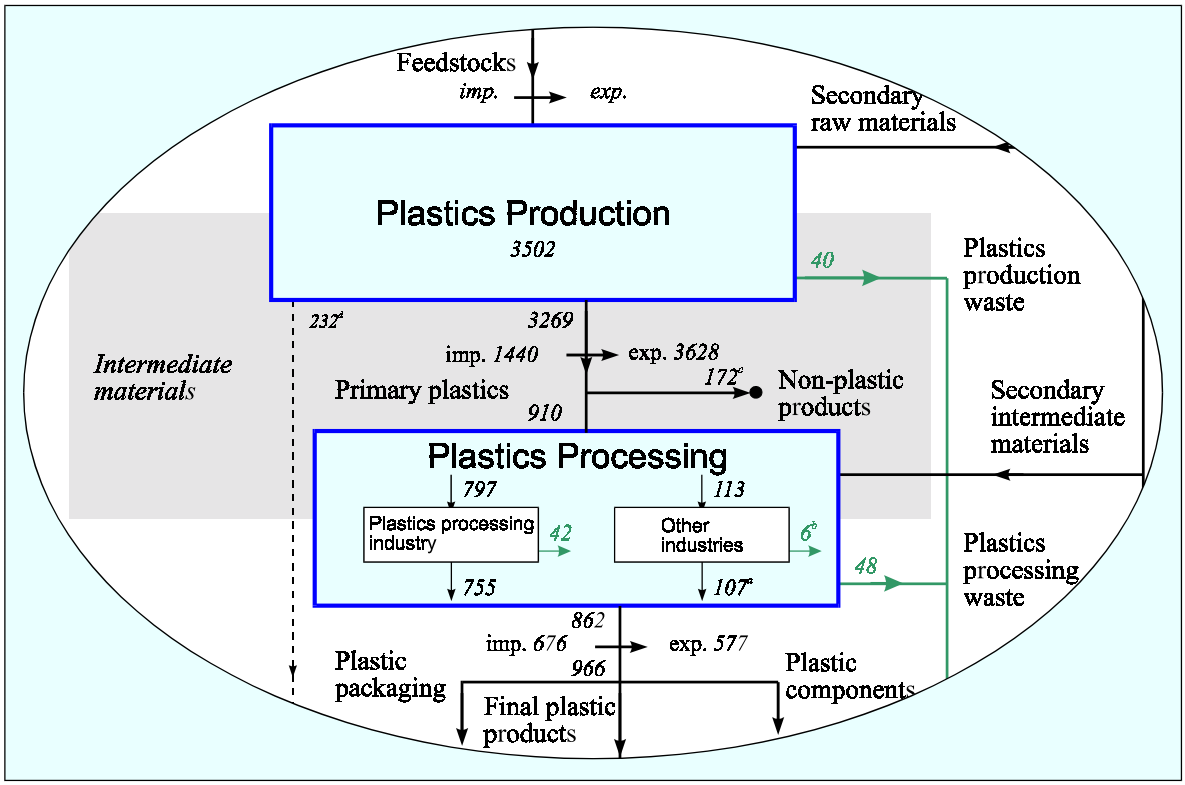

Figure 3 Aggregated results of the supply and use analysis. [a]Including 62 ktonnes of confidential supplies. [b]Plastic processing waste from 'other industries' was calculated using the same waste percentage (6.4%) as the plastics processing industry. [c]Primary plastics use for producing non-plastic products consists of the use of primary plastics by the industries of textiles, pigments, paint, ink, detergents and glues. [d]Primary plastics used to produce packaging, components and final products which are not further traded, but which are used in the producing industry itself.

3.3.2 The final consumption analysis

Above, only *direct* supplies and uses of primary plastics and plastic products were determined. However, a lot of plastic products are used indirectly: they serve as packaging or as component for other goods and change hands once more before reaching the final consumer, together with those goods. In order to follow packaging and components to their final consumer, we developed the final consumption analysis. In this analysis plastic packaging and components used by industries are allocated to their products, and subsequently to the users of those products.

Stepwise description of the final consumption analysis

In this paragraph we stepwise describe the application of the final consumption analysis to the flow of plastics through The Netherlands in 1990.

(1) Evaluation of the purpose of use of primary plastics and plastic products

From the plastics processing stage plastics follow different routes through the process scheme. In the following calculations this has to be taken into account. From Figure 2 it can be seen that plastic products are used for three different purposes: as final product, as packaging or as component. Primary plastics are used to produce plastic products or non-plastic products. However, because some industries use primary plastics to produce packaging, components or final products for their own use, also the three purposes of use for plastic products are applied to primary plastics. In Figure 2 these primary plastics follow the dotted lines (see also Chapter 2). Table 9 summarises the different purposes of use of primary plastics and plastic products.

Table 9 Purposes of use of primary plastics and plastic products

Purpose of use:	**Primary plastics**	**Plastic products**
production of plastic products	X	
production of non-plastic products	X	
use as packaging	X	X
use as component	X	X
use as final product	X	X

In our approach the use of primary plastics and plastic products by each industry is examined and the purpose of use is estimated. We assume all purchases of primary plastics and plastic products by service sectors and final demand categories to be final consumption, because these sectors do not hand over many products[9].

From Table 7 it can be seen that, after the corrections, still 60 ktonnes of confidential supplies of plastic products remain. Because it is not visible which industries are the suppliers of those products, it is impossible to see which industries use primary plastics to produce them. We only know that it is *not* the plastics processing industry. However, for further calculations it is important to assign the uses of primary plastics for producing plastic products, in order to avoid double counting. We use an alternative method to assign primary plastic use for producing plastic products by ‘other industries than the plastics processing industry. First we assign the primary plastic use by these ‘other industries’ to the four other categories (Table 9), neglecting ‘use for producing plastic products’. The result of this is that the 113 ktonnes of primary plastics use by other industries than the plastics processing industry (Figure 3) that should be in this category, are assigned to ‘use as packaging’ and ‘use as component’ instead. So too much primary plastics are assigned to the latter two categories. Next these categories

[9] From the use and supply tables it is not possible to read the materials and products delivered by trade (a service sector), so primary plastics and plastic products used in trade cannot be assigned to the products supplied by this sector.

are adjusted by lowering all uses of primary plastic by other industries than the plastics processing industry with a percentage which reduces the total use by 113 ktonnes.

The physical plastics use table is split into five plastics use tables, one for each purpose of use (as distinguished in Table 9). The totals of the plastic use tables concerning 'use as final product', 'use as packaging' and 'use as component' can be read from Table 10.

Table 10 Purpose of use of primary plastics and plastic products; totals for The Netherlands in 1990

	Use as final product [ktonne]	**Use as packaging** [ktonne]	**Use as component** [ktonne]	**Total use** [ktonne]
Primary plastics	**104**	**4**	**125**	**232**
Plastic products:				
Plastic building materials	41	0	6	47
Plastic industrial components	4	0	29	33
Plastic films and sheets, cellular	7	8	6	22
Plastic films and sheets, reinforced	10	0	8	18
Plastic films and sheets, others	19	109	26	153
Plastic tubes	56	0	21	77
Plastic rods and profiles	12	0	20	31
Plastic floor covering	41	0	0	41
Plastic furniture	28	0	0	28
Plastic lighting	3	0	0	3
Plastic packaging	109	203	0	313
Refuse bags	18	0	0	18
Adhesive tape	12	0	3	15
Plastic office and school supplies	15	0	0	15
Other plastic products	152	0	0	152
Plastic products, total	**526**	**321**	**119**	**966**

(2) Construction of the goods supply and use tables

From the original supply and use tables, which contain both goods and services, the rows referring to the supply and use of services are removed, because the deliverance of plastics is only connected to the deliverance of goods, not to the deliverance of services. What remains are the goods supply and use tables.

(3) Construction of the percentage goods supply table

For each industry, all supplies of goods are divided by the total supply of goods by that industry, in order to form the percentage goods supply table.

(4) Allocation of plastic packaging and components to goods supply

The percentage goods supply table is multiplied by the plastic use tables concerning 'use as packaging' and 'use as component'. By this means, for each industry the primary plastics and plastic products used as packaging or as component are allocated to the goods supplied by

that industry. The calculations result in sixteen tables (one for primary plastics and fifteen for plastic products) representing the assignment of primary plastics and plastic products used as packaging and another sixteen tables representing the assignment of primary plastics and plastic products used as component.

(5) Calculation of the plastic packaging and plastic component contents of goods
Generally, goods are supplied by more than one industry, as can be read from the supply and use tables. Because each industry has its own pattern of packaging and components use, amounts of packaging and components assigned to the same good supplied by different industries are not exactly equal. However, for further calculations unambiguous plastic packaging and plastic component contents for each good are needed. This is achieved by dividing the total amount of primary plastics and plastic products assigned to each good by the total national supply of that good. By this means, average plastic contents of all goods are obtained, in which differences between industries are eliminated.

Again, confidential supplies cause a complication. Because in the calculation method primary plastics and plastic products used as packaging or component are assigned to *all* of the industry's supplied goods, also its *confidential* goods become a plastic content. It is, however, unknown which goods are involved. So it is also unknown which goods the packaging and components have to be assigned to. We solved the problem by using an alternative allocation method for those confidential goods. From the column 'confidential' in the supply table the total national amount of confidential supplies of each good is deduced. We divide the total amount of plastic packaging and components assigned to the confidential goods of all industries together proportionally between the total domestic supplies of these confidential goods.

(6) Assignment of plastic packaging and components to the final consumers
By multiplying the use table of goods by the plastic contents obtained above, the primary plastics and plastic products used as packaging or as component are assigned to the final consumers. This results in two tables, representing the *'indirect final consumption'* of plastics, as packaging and component respectively. Imports and exports of products are multiplied the same way by the plastics contents, in order to assess the *indirect* imports and exports of plastics. We assume that imported goods are comparable with respect to plastic packaging and component contents to goods manufactured domestically and that goods produced for exports are comparable to goods for the domestic market.

Results of the final consumption analysis

The aggregated results of the final consumption analysis are presented in Table 11 to Table 14. Table 11 provides information on the final consumption of the primary plastics and plastic

products divided between direct final consumption, indirect final consumption as packaging and indirect final consumption as component. Table 12 shows the direct and indirect final consumption of plastics by consumer groups. In Table 13 the indirect final plastics consumption is displayed, divided between the categories of goods they were applied to. Finally, Table 14 shows the indirect imports and exports of primary plastics and plastic products, used as packaging or as component.

Table 11 Direct and indirect final consumption of primary plastics and plastic products in The Netherlands in 1990

	Direct final consumption [ktonne]	**Final consumption as packaging** [ktonne]	**Final consumption as component** [ktonne]	**Final consumption, total** [ktonne]
Primary plastics	**104**	**4**	**162**	**270**
Plastic products:				
Plastic building materials	41	0	9	49
Plastic industrial components	4	0	39	43
Plastic films and sheets, cellular	7	11	7	26
Plastic films and sheets, reinforced	10	0	11	20
Plastic films and sheets, others	19	119	30	168
Plastic tubes	56	0	26	81
Plastic rods and profiles	12	0	25	37
Plastic floor covering	41	0	0	41
Plastic furniture	28	0	0	28
Plastic lighting	3	0	0	3
Plastic packaging	109	185	0	294
Refuse bags	18	0	0	18
Adhesive tape	12	0	3	15
Plastic office and school supplies	15	0	0	15
Other plastic products	152	0	0	152
Plastic products, total	**526**	**315**	**149**	**991**
Total	**630**	**319**	**312**	**1260**

Table 12 Direct and indirect final consumption of plastics in The Netherlands in 1990, by consuming sector

	Direct final consumption [ktonne]	**Final consumption as packaging** [ktonne]	**Final consumption as component** [ktonne]	**Final consumption, total** [ktonne]
Agriculture and fishing	3	6	1	11
Industry	54	105	101	260
Building	171	19	31	220
Trade	86	6	8	100
Other services[a]	106	35	28	170
Households	97	112	72	281
Investments[b]	82	31	64	176
Stock increase	31	5	7	42
Other final demand categories	0	0	0	1
Total	**630**	**319**	**312**	**1260**

[a]Including catering, government, education, banking and health services; [b]Purchases of durable capital goods (lifetime 1 year or more).

Table 13 Indirect final consumption of plastics in The Netherlands in 1990, by product type

	Final consumption as packaging [ktonne]	**Final consumption as component** [ktonne]	**Indirect final consumption, total** [ktonne]
Food and smokers' requisites	96	1	97
Textiles and fashion articles	14	13	27
Paper and printers' articles	22	23	45
Building materials and interior	24	34	58
Energy carriers	4	4	8
Chemical products[a]	54	10	65
Metal products and machinery[b]	66	148	213
Means of transportation	19	38	57
Other products[c]	19	41	60
Total	**319**	**312**	**630**

[a]Including soaps, cosmetics and medicines; [b]Including household appliances; [c]Photographic materials, clocks, toys, camping equipment, sports equipment *etc*.

Table 14 Indirect imports and exports of plastics as packaging or as component to and from The Netherlands in 1990

	Imports [ktonne]	**Exports** [ktonne]
As packaging	189	175
As component	248	165
Total	**437**	**340**

With the results of the final consumption analysis, the scheme of plastic flows in The Netherlands (Figure 3) can be completed. The result is shown in Figure 4.

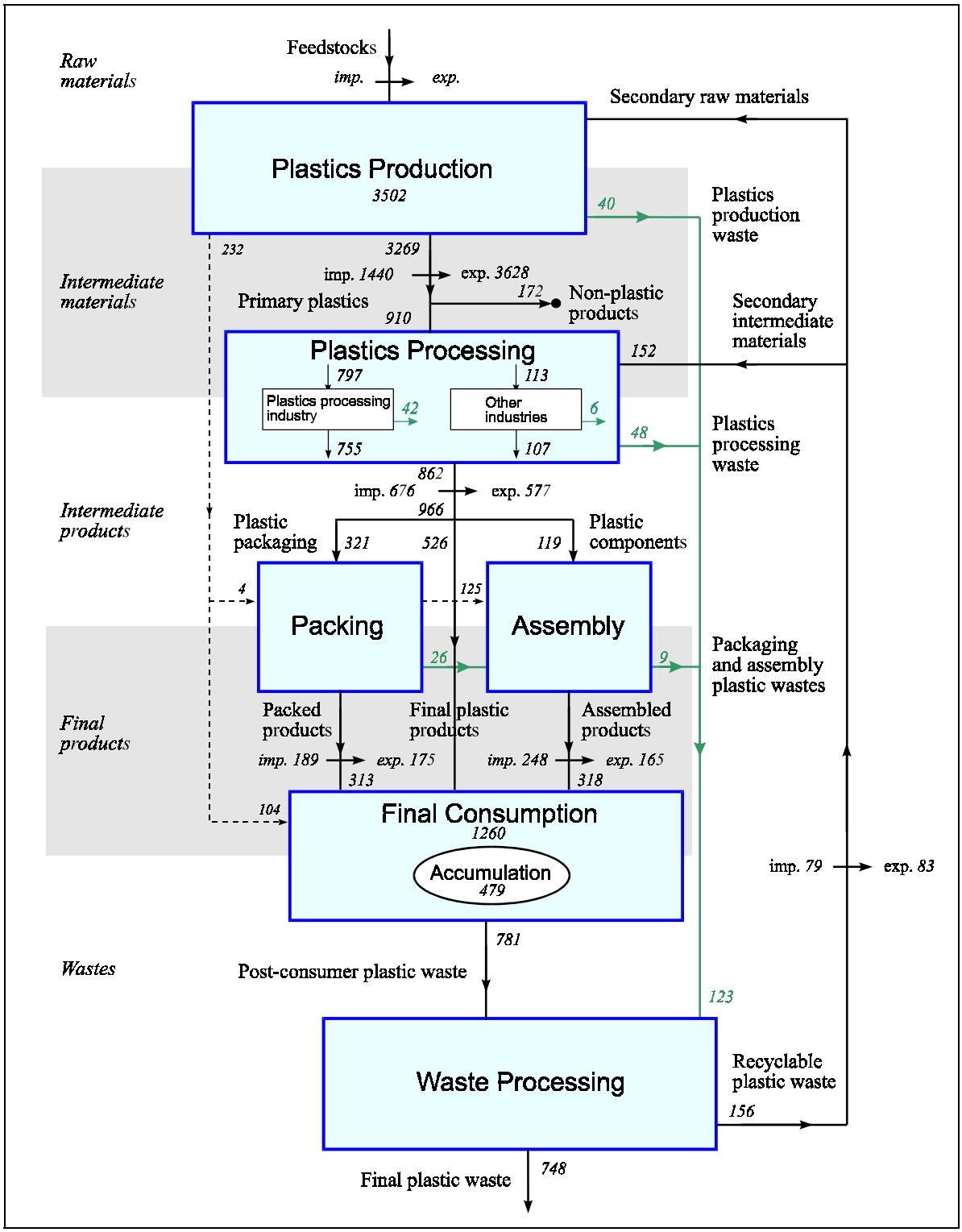

Figure 4 Flow of plastics in The Netherlands in 1990 [ktonne], based on aggregated results obtained using the STREAMS method. All figures concern primary plastics content; secondary materials content is not included.

3.4 Discussion

In this section the applicability of the STREAMS method is discussed. In paragraph 3.4.1 the usefulness of the use and supply tables of The Netherlands as data source for material flow analysis is discussed. The main results are discussed in paragraph 3.4.2. In paragraph 3.4.3 we attempt to validate the method by comparing its results to the results of other studies. Subsequently, in paragraph 3.4.4, we discuss a number of methodological aspects that may affect the accuracy of the results and estimate the contributions to the mean deviation of the results. Finally, in paragraph 3.4.5, the total mean deviation of the results is calculated.

3.4.1 Usefulness of The Netherlands' use and supply tables for material flow analysis

Because the STREAMS method starts from the country's supply and use tables, the minimum aggregation level of the results depends on the aggregation levels of these tables. This applies to the goods, the core materials, the core products and the industries and consumers that are discerned. The supply and use tables of The Netherlands proved to be sufficiently detailed for the study of plastic flows: 237 different industries and consumers are discerned, using and supplying 529 different goods, 15 of which can be identified as plastic products. From the other hand only one category 'primary plastics' is discerned, which contains all primary plastics. This makes it impossible to discriminate between primary plastic types (e.g polyethylene, polypropylene). Although a category 'plastic waste' is discerned, it is not usable for the analysis because it only comprises plastic wastes that are traded and is, therefore, incomplete.

3.4.2 Results

From our calculations it follows that the total final consumption of plastics in The Netherlands in 1990 amounted to 1260 ktonnes. Table 11 shows that 630 ktonnes of these were consumed directly, as final product, 319 ktonnes as packaging and 312 ktonnes as component. Table 11 also says something about the route that was followed by the plastics till final consumption. Almost 80% of final plastics consumption appears in Table 11 as 'Plastic products'. These plastics were used by one industry to produce plastic products, which were subsequently sold to another industry that used them as final product, as packaging, or as component. The remaining 20%, which appear as 'primary plastics', are plastic products that were used as final product, as packaging material, or as component by the same industry as the industry that produced them from primary plastics. This means that these industries produced their own final products, packaging and components. As can be seen from Table 11, this is often the case with components: 52% of components were 'home made' by the industries that built them into their products. This is in contrast to packaging, of which only

1% was 'home made' by the industries that used them to pack their products. So almost all plastic packaging is bought from other industries. The 104 ktonnes of primary plastics in the column 'Direct final consumption' of Table 11 are primary plastics used by service sectors that do not sell products. From the physical plastics use table it can be derived that these encompass 56 ktonnes of primary plastics (mainly PUR) used in building and 22 ktonnes of primary plastics used in research.

According to Table 11 the direct final consumption of plastic packaging in The Netherlands in 1990 (plastic packaging used directly by service sectors and final demand categories) amounted to 109 ktonnes. Table 11 also shows that the indirect final consumption of plastic packaging amounted to 319 ktonnes. So the total final consumption of plastic packaging is calculated at 428 ktonnes, which is 34% of total final plastics consumption. Components make up 25% of total final plastics consumption. The remaining 41% can be roughly divided into 'consumer products'[10]: 18% and 'building materials and others': 23%.

Table 12 shows that the sector 'households' is the largest final consumer of plastics. The final plastics consumption of the sectors 'building' and 'industry' is also considerable. From Table 13 it can be seen that 30% of plastic packaging finally consumed in The Netherlands in 1990 was used to pack food and smokers' requisites; 21% was used to pack metal products and machinery (including household appliances). It is not very surprising that also a large part of components (47%) were used for metal products and machinery.

3.4.3 Comparison to other studies

In order to get an idea of the accuracy of the results of a calculation method we can compare them to the results of similar studies. For several reasons comparison of our results to the results of other studies turns out to be very difficult. Firstly, in literature studies on *final consumption* are lacking almost completely. 'Final plastics consumption' data in literature often refer to apparent consumption, calculated as the production of primary plastics plus imports of primary plastics minus exports of primary plastics. The results show that apparent plastics consumption (1142 ktonnes excluding non-plastic products, see Figure 4) differs considerably from final plastics consumption as calculated with the STREAMS method (1260 ktonnes, see Table 11). The difference is mainly caused by differences between imports and exports. As can be seen from Figure 4, direct imports of plastic products exceed exports of plastic products by 99 ktonnes. Also indirect imports and exports differ. The difference between indirect imports and exports of plastic packaging is relatively small (15 ktonnes), but the difference between indirect imports and exports of plastic components is considerable (87 ktonnes). The latter is caused by the fact that The Netherlands houses a relatively small

[10] Furniture, lighting, refuse bags, adhesive tape, office and school supplies and other products

industry of machines and transportation equipment, so a considerable part of the equipment for production and transportation used in The Netherlands is imported. Another difference between apparent consumption and final consumption lies in the fact that in apparent consumption processing waste is included, whereas in final consumption it is not.

As a second problem in comparing the results of two or more studies, we face the fact that every study uses its own, often implicit definitions, subdivisions and reference years. The fact that there are many material flows through society, following a widespread network of routes, being used by many users for many purposes, adds to the confusion among authors, making literature hard to interpret correctly. In the case of plastics a number of factors forms a further complication. It makes a difference whether data concern plastics with or without additives, plastic products with or without non-plastic parts, plastic waste including or excluding dirt and water and 'primary' plastics with or without regranulate. Data sources that are obscure concerning these aspects are still harder interpretable. Because of these difficulties only total plastic packaging use can be compared to the results of other studies[11].

The direct use of plastic packaging in The Netherlands in 1990 can be derived from Table 10. According to Table 11, 109 ktonnes of plastic packaging were used as final product. Furthermore, 321 ktonnes of other plastics were used as packaging by The Netherlands' industry. So the total use of plastic packaging amounted to 430 ktonnes. This figure comes close to amount of 41% * 992 = 407 ktonnes of plastics used for packaging, as reported by the APME (1992). As stated above, total *final* consumption of plastic packaging amounted to 428 ktonnes. Because this amount refers to a primary plastic content of plastic products of 78%, the total weight of plastic packaging that is finally consumed in The Netherlands in 1990 is calculated at about 550 ktonnes. In literature final consumption of plastic packaging in The Netherlands is estimated at 470 ktonnes in the year 1988 (Worrell *et al.*, 1995, Blonk *et al.*, 1992). The difference between our calculations and this estimate from literature is mainly accounted for by the growth of plastic consumption between 1988 and 1990. In this period, plastics consumption in The Netherlands has grown by 13% (K+R, 1993). So the estimate of 470 ktonnes in 1988 corresponds to about 530 ktonnes in 1990. Our result of about 550 ktonnes compares fairly to this estimate.

Other data in literature, which could be used to validate the method, are not available. Therefore, in the following paragraphs we estimate the mean deviation of the results, based on a theoretical analysis of factors that may affect the accuracy of the results.

[11] In comparing the results of the STREAMS method to data in literature, one has to bear in mind that all results of the STREAMS method concerning plastic products refer to their primary plastics content. In the case of plastic flows in The Netherlands, we calculated an average primary plastics content of 78%. This percentage has to be accounted for, because data in literature generally concern the total weight (100%) of plastic products.

3.4.4 Factors affecting the accuracy of the results

In this paragraph we discuss the most important factors that affect the accuracy of the results obtained from application of the STREAMS method to plastic flows in The Netherlands. Besides, we give an estimate on the mean deviations they cause to the results. A general property of the results is that their accuracy is higher if presented on a higher aggregation level. Our estimates apply to the lowest aggregation level: individual plastic materials and products used as packaging or component for individual goods that are used by individual industries.

The supply and use analysis

The supply and use analysis contains two steps that may affect the accuracy of the results: the conversion of the plastics use and supply tables from monetary units to physical units and the calculation of the primary plastics content of plastic products.

Conversion of the plastics use and supply tables from monetary to physical units

As a rough approximation for the conversion of the monetary plastic use and supply tables into their physical equivalents, we used The Netherlands' statistics of foreign trade, which are expressed in monetary as well as in physical units. This makes it possible to calculate mean export prices per plastic material or product. Assuming that these prices do not differ significantly from mean prices on the domestic market, we applied them to all uses and supplies of plastic products. Statistics Netherlands has also made an effort to convert the monetary plastics use and supply tables into physical units, using a more sophisticated method, using different prices for each industry and balancing principles (Konijn *et al.*, 1995, 1996). We used the results of this approach, published in an aggregated form, to validate our conversion method.

Comparison of the results of both conversion methods shows that the results, on a high aggregation level, *e.g.* the total use and supply of plastic products by all industries, are fairly matching. For the use and supply of all plastic materials and products together by individual industries we observed a mean deviation of ± 9%. For the use and supply of individual plastic materials and products by all industries together we observed a mean deviation of ± 5%. On lower aggregation levels some results are less promising. For the separate plastic products and for individual industries, the agreement differs. For the plastic product categories 'plastic packaging' and 'plastic films and sheets, others', the results are fairly corresponding (deviations <10%). Some other plastic product categories, like 'plastic building materials' and 'plastic industrial components', show deviations of up to 60%. There are two reasons for this: firstly the fact that the calculation of mean export prices is rather difficult because of mismatches between the plastic product categories discerned in the use and supply tables on

the one hand and the product categories in the statistics of foreign trade on the other hand. The second reason is that in practice there may be differences between mean export prices and prices on the domestic market. Each product category consists of a range of products with different prices. Therefore it is possible that exported products have different prices as products of the same product category produced for the domestic market. For the use and supply of individual plastic materials and products by individual industries we observed a mean deviation of ± 19%.

Calculation of the primary plastics content of plastic products

We calculated a mean primary plastics content of plastic products of 78%[12], the rest consists of additives, other materials and recycled plastics. We used this mean value to calculate the primary plastics content of all plastic products. By doing this, additives, other materials and recycled plastics were spread over all plastic products. In practice, however, plastic products contain different contents of additives, other materials and recycled plastics. We estimate that this causes a mean deviation of ± 10%.

The final consumption analysis

In the final consumption analysis five possible sources of deviation can be discerned, which will be discussed in this paragraph.

Evaluation of the purpose of use of plastic materials and products

We estimated the purpose of use of plastic materials and products based on common sense and general knowledge on industries and the goods they produce. Of course, mistakes are possible. We estimate the mean deviation caused by this issue at ± 10%.

Allocation of packaging and components to produced goods

In the STREAMS method the allocation of core packaging and components is necessarily based on a monetary basis, because the –monetary– percentage goods supply table is used. In practice, however, packaging and components contents of goods are probably more closely related to weight than to economic value. Furthermore, because the method allocates packaging and components used by industries to *all* of their produced goods, on a minor scale some strange results are obtained, like living cattle packed in plastic, caused by the use of plastic packaging –for packing vegetables– in agriculture. We estimate the mean deviation caused in the allocation step at ± 15%.

[12] If secondary plastics were included, this would be 96%.

Confidential supplies

The supply and use tables of The Netherlands contain relatively much omissions caused by confidentiality. In The Netherlands 14% of all supplies are confidential. The reason for this is that The Netherlands is a small country with in some industries only one or a few companies, the sales of which are not published in national statistics. In STREAMS this causes some complications. Firstly, because of the existence of confidential supplies of plastic materials and products in the supply and use tables, it is not possible to construct plastics supply and use tables without 'guessing' which industries are the suppliers. Secondly, because plastic packaging and components are allocated to all products of the industries that use them, also the industries' confidential supplies become a plastic content. From the calculations it can be derived that 13% of the plastic packaging and 22% of the plastic components are allocated to confidential supplies. As it is unknown which goods are supplied confidentially per industry, it is also unknown which goods these packaging and components must be allocated to. For these goods we had to add an alternative calculation step to the STREAMS method. This step divides the total amount of plastic packaging and components that is allocated to the confidential supplies of all industries together between the confidentially supplied goods. We estimate that this issue causes a mean deviation of ± 10%. If the STREAMS method is applied to other, larger countries –with less confidential supplies– this deviation is expected to be much lower.

Calculation of the plastic contents of goods

In STREAMS the calculation of plastic contents of goods is based on the supply and use tables, which are a representation of the national industry. Imported products are assumed to have the same composition and the same packaging content as domestically produced products. A result of this is that products that are not produced domestically, but which are fully imported, receive no plastic content. The results of our calculations show that in The Netherlands this is the case for, for example, refrigerators. For goods that are largely produced in The Netherlands this issue plays a lesser role. Because this issue plays a role for only a limited number of products, we expect a mean deviation of ± 5%.

Trade

In practice, trade is involved in many supplies and uses. The supply and use tables, however, do not state in which supplies and uses trade is involved. Therefore it is impossible to allocate plastic packaging and components used in trade to the products that are traded. Table 12 shows that 86 ktonnes of plastics were used in trade. In the calculations they end up as final consumption in trade, whereas in reality a part of this amount ends up at the users of the products that are traded. From the other hand, industrial packaging like shrink films, which are used to bundle a number of products and which, in practice, end up in trade, are allocated

to the users of the products traded. These two deviations partly neutralise each other. Because of this we estimate the mean deviation from this issue at ± 5%.

3.4.5 Estimate of the total mean deviation of the results

Above, several factors affecting the accuracy of the results were discussed. All individual mean deviations add up to a total mean deviation. Because the calculations of the method mainly consist of multiplications, the total mean deviation is calculated with the formula:

$$D^2 = \sum_i d_i^{\,2}$$

D = total mean deviation
d_i = individual mean deviations

This way the total mean deviation of model results is calculated at ± 30%. This applies to the lowest aggregation level: individual plastic materials and products used as packaging or component for individual goods, which are finally consumed by individual consumers. Results presented on higher aggregation levels are much more accurate.

3.5 Conclusions

This study shows that the STREAMS method is a powerful tool for the analysis of a country's material flows. It demonstrates that highly detailed information can be obtained on materials flows in all stages of their lifecycle. The method is unique in studying the stage of final consumption, a stage that is largely neglected in literature, but which is the most accurate measure for a country's materials consumption. By applying the method to the flows of plastics in The Netherlands in 1990, we calculated the total final consumption of plastics in the Netherlands at 1260 ktonnes. This is considerably higher than the apparent consumption of 1142 ktonnes that is calculated rather roughly from the production, imports and exports of primary plastics. Therefore we conclude that apparent consumption, although easily calculable, is rather a poor approximation for final consumption.

However, the STREAMS method faces a number of problems that should be solved in order to get more accurate results. We estimate the mean deviation of the results of our analysis on the lowest aggregation level at ± 30%. Results presented on higher aggregation levels are much more accurate. Part of the deviation is caused by factors that are typical for the situation in The Netherlands, like the high amount of confidential supplies. Other factors are inherent to the method, for example the fact that the allocation takes place on a financial basis. A number of factors can be eliminated by refinement of the method. Notably, the conversion

from monetary into physical units and the allocation step can be improved considerably, leading to more accurate results. These improvements will be implemented in the method in a following study, a case study on paper and wood flows in The Netherlands (Hekkert *et al.*, 2000). We expect that these refinements diminish the mean deviation of the results on the lowest aggregation level to about ± 15%.

If the method is applied to other, larger economies, of which the statistics contain less omissions for confidentiality reasons, even smaller mean deviations are expected. On the other hand, if statistical data becomes less detailed, less detailed results are to be obtained. Provided that no major changes take place in statistical data collection and representation, the analysis may be repeated for subsequent years, in order to track changes in plastic uses over time.

3.6 References

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Chapter 4

Energy and CO_2 analysis of the Western European plastics lifecycle[1]

Abstract

We investigate the amount of fossil fuels that is used - as energy source and as feedstock - and the amount of carbon dioxide (CO_2) that is emitted in the Western European lifecycle of plastics. The amount of fossil fuels used *as feedstock* is calculated from a material balance of the plastics lifecycle. The amount of fossil fuels used *as energy source* and the CO_2 emissions that are involved are deduced from an investigation of all major processes that constitute the lifecycle of plastics. These include processes for crudes extraction and processing, alkenes production, intermediates production, polymers production, plastics processing, auxiliary materials production and plastic waste management

From our calculations we conclude that in 1994 the Western European lifecycle of plastics used about 2317 PJ of energy carriers, which is 4.4% of the total Western European consumption of fossil fuels in that year. Feedstock use for plastics production amounted to about 1109 PJ (about half of the total energy use in the lifecycle of plastics). CO_2 emissions from the lifecycle of plastics amounted to about 79.9 Mtonne, 2.3% of the total Western European CO_2 emissions in 1994. Of the stages in the plastics lifecycle that were investigated in this study the largest contributions to the total energy consumption of the plastics lifecycle were found for *plastics production* (28%), *alkenes production* (23%) and *plastics processing* (18%). These stages also produced the largest shares of CO_2 emissions (27%, 17% and 14% respectively).

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4.1 Introduction

Plastics play an important role in society. In 1994, 26256 ktonne of plastics were used in Western Europe (APME, 1996). Moreover, the production of plastics is highly energy intensive, because fossil fuels are both used as feedstocks and as energy sources. Therefore, a large amount of fossil fuels is used in the lifecycle of plastics. The use of fossil fuels promotes the exhaustion of non renewable energy sources and fossil fuels combustion causes carbon dioxide (CO_2) emissions. CO_2 emissions are also caused by plastics waste incineration and other waste processing technologies. In order to combat global warming and the exhaustion of non renewable energy sources, both fossil fuels consumption and CO_2 emissions should be reduced.

In the lifecycle of plastics many materials processing processes are involved. Each process may be investigated in order to find measures to reduce energy consumption and CO_2 emissions. The complexity of the plastics lifecycle makes it difficult to get a quick overview of the energy consumption in and CO_2 emissions from the plastics lifecycle. However, for policies aiming to reduce materials use, energy consumption and CO_2 emissions this overview is necessary in order to get an idea of the relative importance of the different processes in the lifecycle of plastics with respect to these environmental issues. Processes that have large shares in total lifecycle energy consumption or CO_2 emissions potentially enable large reductions and are, therefore, interesting objects for further research.

The aim of this study is to gain insight in the energy consumption and CO_2 emissions of the processes of the plastics lifecycle. It deals with the question how energy consumption and CO_2 emissions are distributed between the processes that constitute the plastics lifecycle. Furthermore, the shares of the energy consumption and CO_2 emissions of the plastics lifecycle compared to total energy consumption and CO_2 emissions in Western Europe are investigated.

In this study we focus on the Western European situation in 1994. The whole plastics lifecycle is investigated, from crudes extraction, via plastics production, plastics processing and consumption to plastic waste management. For all processes involved total annual energy consumption and CO_2 emissions are calculated. The calculated values give insight into the relative importance of the processes in the lifecycle of plastics, with regard to energy consumption and CO_2 emissions.

The plastics lifecycle largely exists of chemical processes that encompass complicated material and energy flows. This makes it difficult to obtain unambiguous data on energy consumption and CO_2 emissions. In literature, few comprehensive studies on energy consumption and CO_2 emissions in the production and processing of plastics are available.

Chauvel *et al.* (1989a,b) have described a large number of processes in the petrochemical industry, including processes for the production of feedstocks for plastics. Although rather old (data refer to 1986), their books are comprehensive sources for information on petrochemical processes, including data on energy requirement and CO_2 emissions. Van Heijningen *et al.* (1992a,b) and, more recently, Patel *et al.* (1996, 1998) have also studied energy use for the production of a number of plastics and their feedstocks. In our study these data sources are reviewed, together with other, less comprehensive data sources on specific processes, in order to obtain input data for our calculations.

Data on energy use and CO_2 emissions in the lifecycle of plastics are also important inputs for life cycle analyses. Databases for LCA calculations like SimaPro (1998) and GEMIS (1998) provide additional data for our calculations. From the other side, our study can be useful in providing bottom-up input data for LCA's on plastic products in Western Europe. The comprehensive studies on energy consumption and CO_2 emissions connected to plastics production by Boustead *et al*. (1993-1995) and BUWAL (1996) are of limited use for our study, because only generic data is presented, combining all processes needed for the production of plastics, whereas for our study we need detailed data on all subprocesses involved.

In section 4.2 we describe the lifecycle of plastics and the method we used to calculate total Western European energy consumption and CO_2 emissions involved in the lifecycle of plastics in 1994. In section 4.3 energy requirements and CO_2 emissions of processes for alkenes production, intermediates production, polymers production, plastics processing, plastic waste management, feedstocks extraction and auxiliary materials production are investigated. Subsequently, the results of the calculations are presented in section 4.4 and discussed in section 4.5. Finally, in section 4.6, conclusions are drawn on the relative importance of the processes in the plastics lifecycle, with respect to energy consumption and CO_2 emissions.

4.2 Methodology

In this section we go into the methodological aspects of our method to calculate the total energy requirement and the total CO_2 emissions from the Western European lifecycle of plastics. First, in paragraph 4.2.1, the lifecycle of plastics is depicted. Next, in paragraph 4.2.2, the system boundaries are given and finally, in paragraph 4.2.3, the calculation method is described in detail.

4.2.1 The lifecycle of plastics

The lifecycle of plastics consists of a number of stages, which are listed in Table 1. Each stage involves a number of processes.

The primary feedstocks for the production of plastics are crude oil and natural gas. Crude oil is extracted from the earth and transported to refineries. In refineries it is distilled into a range of fractions, of which naphtha, liquefied petroleum gas (LPG) and gas oils are used to produce plastics. Natural gas with high ethane content is also used for plastics production.

Naphtha, LPG, gas oils and ethane are used as feedstocks for steamcracking. They are cracked and distilled into four fractions: ethylene, propylene, a C4 fraction containing butenes and butadiene, and a BTX fraction consisting of benzene, toluene and xylenes. Ethylene and propylene are directly used as monomers for the production of polymers. The C4 and BTX fractions are further separation into their components, part of which are also used for the production of plastics. In this study we call these components ‘intermediates’. Other intermediates that are used in the production of plastics are styrene, which is produced from ethylene and benzene, and vinylchloride monomer (VCM), which is produced from ethylene and chlorine.

Alkenes and intermediates are used to produce polymers. In this analysis we discern seven different polymers: Polyethylene (PE, subdivided into Low Density Polyethylene (LDPE), Linear Low Density Polyethylene (LLDPE) and High Density Polyethylene (HDPE)); Polypropylene (PP), Polystyrene (PS), PolyVinyl Chloride (PVC), Polyethylene Therephtalate (PET), ‘other thermoplastics’ and ‘thermosets’.

Polymers are processed into plastic products, using the plastics processing processes indicated in Table 1. After the plastic products have been used, they are discarded and become waste. Different processes are used to handle plastic waste: landfilling, incineration, mechanical recycling, gasification, hydrogenation, pyrolysis and blast furnace injection. A number of these processes uses the energy and / or material content of the plastic waste. Reused materials and energy can be fed back into the plastics lifecycle, reducing the demand for virgin feedstocks and energy carriers.

Table 1 Stages in the lifecycle of plastics and the processes that are involved

Crudes extraction and transport	**Feedstocks production**	**Alkenes production**	**Intermediates production**	**Polymers production**	**Plastics processing**	**Use of final products**	**Plastic waste management**
Crude oil Natural gas	Crude oil distillation - Naphtha - LPG - Gas oil	Steamcracking of naphtha, LPG, gas oil, ethane - Ethylene - Propylene - C4 - BTX	Butadiene Benzene Toluene *p*-Xylene Styrene VCM	PE PP PS PVC PET Other thermoplastics Thermosets	Film extrusion Extrusion coating Sheets extrusion Thermoforming Blow moulding Injection moulding Foaming Tubes extrusion Profiles extrusion Cables extrusion Other processes		Landfilling Incineration Upgrading Blast furnace injection Pyrolysis Gasification Hydrogenation Mechanical recycling

4.2.2 System Boundaries

In this study we focus on the plastics lifecycle in Western Europe, consisting of the European Union[2] plus Norway and Switzerland. For all processes discerned we describe data on energy consumption and CO_2 emissions that are representative for this region. If possible, we use average values for all process variants that are used in Western Europe. In other cases we use data concerning the process variant that is used most extensively. These data are assumed to be representative for the Western European situation.

Thousands of plastic types and sub-types are produced and used in Western Europe. However, in this study only the lifecycle of a restricted number of these plastics can be assessed. Nevertheless we aim at presenting a general overview of the energy use and CO_2 emissions from the Western European plastics lifecycle. Therefore, we first focus on the so-called bulk plastics, the plastics that are produced and used in large quantities: PE, PP, PS, PVC and PET. These plastics account for 75% of western European plastics consumption (APME, 1996). Next we divide the other plastics into two groups: 'other thermoplastics' and 'thermosets'. For each of these groups a plastic type with a large share is chosen as representative for the whole group. For the group of 'other thermoplastics', Acrylnitril Butadiene Styrene (ABS) is chosen as representative, whereas Polyurethane (PUR) is chosen as representative for the group of 'thermosets'.

In Table 1 the main processes involved in the lifecycle of plastics are presented. We investigate in more detail the production of alkenes, intermediates and polymers, the processing of plastics and the management of plastic waste. These processes are almost exclusively used for the production and processing of plastics. For other processes the link to plastics production and processing is less tight, because only a limited part of the products obtained is used as feedstock for plastics. Hence we studied these processes in less detail. This applies to feedstocks extraction and production, as well as the production of auxiliary materials that are used in plastics production and processing, *e.g.* chlorine, oxygen, nitric acid, methanol and others. Because auxiliary materials are used in relatively limited amounts, the influence of possible inaccuracies in the data on the results of the calculations is expected to be small. We do not investigate possible energy use and CO_2 emissions during the stage in which the plastic products are used by the consumer.

During the production of plastics additives are added to enhance processability, stability *etc*. However, additives, like plasticisers, stabilisers, fillers and lubricants, generally cover a

[2] Austria, Belgium, Luxembourg, Denmark, Finland, France, Germany (including the former German Democratic Republic), Greece, Ireland, Italy, The Netherlands, Portugal, Spain, Sweden and the United Kingdom.

relatively small part of material inputs. General purpose PE and PP have additive contents beneath 3%, PS and PET beneath 5%. Only for PVC additives can make up a considerable part of material inputs: up to 15% (BUWAL, 1996). Because of the small additive content of plastics and the huge amount of different additives used, they are not investigated in this study[3]. For the same reason we did not investigated the production of some auxiliary materials of which small amounts are needed for the production of plastics. These are Sodium Chloride (needed to produce PUR), Sodium Hydroxide (NaOH) and Calcium Oxide (CaO), both needed to process mixed plastic waste.

Note that transport of material takes place between all subsequent processes. However, energy requirement for transportation is generally very limited in comparison to energy requirement for production (Patel *et al.*, 1998). In our study transport energy is not taken into account, except for transports of crude oil from oil producing countries to Western Europe, because of the long distances involved.

4.2.3 The calculation method

In our assessment we examine all processes involved in the lifecycle of plastics. For each process, data on materials inputs and outputs, energy inputs and outputs, as well as CO_2 emissions per tonne of product are collected. The data on material inputs and outputs are used to construct the material balance of the Western European lifecycle of plastics in 1994. The materials balance shows the routes that are followed by the materials, from feedstocks extraction to waste management.

The energy requirements of the processes in the lifecycle of plastics are subdivided into fuel oil, natural gas, steam and electricity requirements. Some processes produce excess heat that leaves the process in the form of steam or electricity. In the calculations steam and electricity production are treated as negative energy requirements. All energy flows are expressed in Gigajoules (GJ). Energy contents of fuels are based on the lower heating values (LHV) that are listed in Table 2.

[3] Because the calculations assume a ‘pure’ plastic content of 100%, additives are replaced by ‘pure’ plastics.

Table 2 Lower heating values (LHV) as used in this study

	LHV [kJ/g]=[GJ/t]
Methane	50.0
Ethane	47.5
Propane	46.3
Benzene	40.6
Toluene	40.9
Xylene	41.2
Ethylene	47.2
Propylene	45.8
Butadiene	45.5
Methanol	21.1
Carbon monoxide	10.1
Hydrogen	120.0
Naphtha	44.0
Gas oil	42.7
LPG	46.0
Crude oil	42.7
Fuel oil	40.5
Coal	29.7
Lignite	21.0
Mixed plastic waste	38.2

Some processes produce fuels as by-products. This is most obvious with steamcracking, which produces a large amount of products that have little commercial value and that are, therefore, regarded as fuels. This means that the net consumption of feedstocks for the production of plastics equals the total feedstocks input of the plastics lifecycle minus the total production of fuels as by-products of processes of the plastics lifecycle. If fuels produced as by-products are used to fulfil (part of) the energy requirement of the process that produces them, we speak of 'internal combustion' (*i.e.* hydrocarbons that are imported into the process as feedstocks, but that are finally used as fuels). Total (direct) energy requirement of processes equals fuel oil requirement + natural gas requirement + steam requirement + electricity requirement + internal combustion.

The energy carriers that are used in the processes of the plastics lifecycle (fuel oil, natural gas, steam and electricity) are produced by processes that require energy as well. A detailed study on energy use and CO_2 emissions of energy production and conversion is beyond the scope of this study. Therefore we use a simplified method to account for the energy needed for the production of the energy carriers that are used in the plastics lifecycle. This method is described by Van Heijningen *et al.* (1992a,b). In their approach the use of energy carriers is multiplied by energy intensities (>1) to include the energy used as energy sources in the production of these energy carriers. A description of energy intensities and their derivation is given in the appendix. Each energy carrier (fuel oil, natural gas, steam or electricity) has its specific energy intensity. We use two different energy intensities for each energy carrier: a

first order energy intensity and a first-and-second order energy intensity. The first order energy intensity accounts for the primary energy needed for the production of steam and electricity. The first-and-second order energy intensity additionally accounts for the primary energy needed for fuels extraction and processing. Table 3 summarises the energy intensities that were used in this study.

All processes result in the production and emission of CO_2. Some CO_2 emissions are inherent to the reaction mechanism of the process. These are called process CO_2 emissions. The largest part of CO_2 emissions, however, is due to the combustion of fuels and is, therefore, connected to the use of energy carriers. The amount of CO_2 that is produced and emitted is calculated from the use of energy carriers and the CO_2 emission factors of these energy carriers. A description of CO_2 emission factors can be found in the appendix. Analogous to the energy intensities we use first and first-and-second order CO_2 emission factors. First order CO_2 emission factors are used to calculate the (direct) CO_2 emissions from fuels combustion and steam and electricity production. First-and-second order CO_2 emission factors are used to include the CO_2 emissions from fuels extraction and processing (including the fuels used for steam and electricity production). The CO_2 emission factors that are used in this study are given in Table 3.

Table 3 Energy intensities and CO_2 emission factors of energy carriers

Energy carrier	**1st order energy intensity** [J/J]	**1st and 2nd order energy intensity** [J/J]	**1st order CO_2 emission factor** [kg / GJ]	**1st and 2nd order CO_2 Emission factor** [kg / GJ]
Fuel oil	1	1.07	73	88
Natural gas	1	1.05	56	57
Steam	1.11	1.19	74	82
Electricity	2.36	2.71	103	134

For each process the energy requirements and CO_2 emissions per tonne of product are analysed. The resulting figures are multiplied by the amount of products produced[4] in Western Europe, leading to total energy requirements and CO_2 emissions per process. Adding all energy requirements and CO_2 emissions together leads to total energy requirement and total CO_2 emissions of the Western European plastics lifecycle.

[4] For Western Europe as a whole, net imports or exports of most products (except crude oil and natural gas) are negligible. This means that, for most products, production virtually equals consumption . Therefore, for a number of processes, for which data on the production is lacking, we use consumption data as approximate.

4.3 Process descriptions

In this section the main processes in the plastics lifecycle are described, with emphasis on energy requirement and CO_2 emissions. The process descriptions pretend to be representative for the Western European situation in the mid-nineties. For each process there are in practice differences in process parameters and feedstock compositions. Therefore the values given in this section should be interpreted as mean values. Although improvements of existing processes can contribute to a decrease of the amount of energy required by the plastics lifecycle, they are not taken into account in this study.

In the respective paragraphs of this section we subsequently investigate the production of alkenes (paragraph 4.3.1), intermediates (paragraph 4.3.2), polymers (paragraph 4.3.3), plastic products (paragraph 4.3.4) and the management of plastic waste (paragraph 4.3.5). Finally, in paragraph 4.3.6, the production of feedstocks and auxiliary materials is discussed.

4.3.1 Alkenes production

In this paragraph processes are analysed that convert a feedstock (naphtha, gas oil, LPG or ethane) into the alkenes ethylene and propylene and a number of other fractions.

Up to now, ethylene has been the most valuable alkene. During the last decade, however, the demand for propylene has grown rapidly, as an effect of the growing demand for polypropylene (PP). In 1994 the Western European ethylene production amounted to 17500 ktonne (Zehnder, 1998). About 55% of ethylene was used for polyethylene production (Zehnder, 1998). Some other uses for ethylene are: vinyl chloride, ethylene oxide, ethanol and ethylbenzene. In 1994, propylene production amounted to 11500 ktonne. About 50% of propylene was used for polypropylene production. Other uses for propylene are: isopropanol, acrylnitril and propylene oxide.

Alkenes can be produced using several processes and feedstocks. All processes have in common that they produce a range of products and by-products. The shares of the different output products depend on the process and feedstock used and, on a minor scale, on the process parameters. Currently, in Western Europe steamcracking is the process mostly used to produce monomers. Several feedstocks are used: naphtha, gas oil, LPG and ethane. In this study steamcracking of naphtha, gas oil, LPG and ethane is investigated. These comprise about 95% of alkenes production in Western Europe.

Steamcracking

In the steamcracking process a feedstock (naphtha, gas oil, ethane or LPG) is heated to 800-900°C in the presence of steam. By this procedure long molecules fall apart, resulting in a mixture of shorter molecules. This mixture is quenched to stop the reaction, compressed, dried and further chilled for distillation. In this way various valuable products are obtained: ethylene, propylene, a C4 fraction containing butenes and butadiene and pyrolysis gasoline (BTX) from which benzene, toluene and xylenes can be produced. The process also produces some by-products with limited market value: a mixture of gasses (methane and hydrogen), which is used as fuel for the process, and a mixture of higher carbons, which can also be used as fuel for the process, or sold as pyrolysis fuel oil. Furthermore, ethane and propane are produced, which are recycled to the reactor. Recycle streams are about 67%, 14%, 5% and 4% of feedstock input for ethane, LPG, naphtha and gas oil cracking respectively (Stratton *et al.*, 1983). This corresponds to single pass conversion rates[5] of about 60%, 88%, 95% and 96% respectively.

A breakdown of feedstocks used in Europe to produce ethylene is shown in Table 4. In Western Europe, naphtha is the main feedstock for steamcracking, in contrast to the US, where ethane is mostly used. A part of the crackers in Western Europe have the possibility to switch between feedstocks. The majority of these 'flexible crackers' can either use naphtha or gas oils. Some of them can also use LPG, but, due to limited storage facilities of gaseous LPG, opportunities are limited (Zehnder, 1998). Flexible crackers demand larger investments but have the possibility to use the feedstock which is cheapest at the moment of processing, or which produces the most valuable output mix. In this study we discern four different plants: one for each feedstock. In order to limit the number of different plants to be modelled we do not discern flexible crackers. Although the energy use of flexible crackers may differ slightly from the energy use of crackers that can only use one feedstock, this difference is expected to be marginal compared to the differences caused by the use of different feedstocks.

Table 4 Breakdown of feedstocks for ethylene production in Western Europe in 1994 (Zehnder, 1998)

Feedstock	**[%]**
Naphtha	64
Gas oils	17
LPG	11
Ethane	8

The shares of the output products of steamcracking highly depend on the feedstock used. The yield of the most valuable product, ethylene, increases in the direction gas oil, naphtha, LPG,

[5] The single pass conversion rate is the percentage of feedstock that is converted in a single pass through the reactor into output products. It is calculated using the following formula: conversion rate = 100 / (100 + recycle rate) * 100%

ethane (see Table 5). Yields of the second valuable product, propylene, are about 0.6, 0.5 and 0.4 in proportion to ethylene yields for gas oil, naphtha and LPG cracking respectively, whereas ethane cracking hardly delivers any propylene. Exact yields vary somewhat with the composition of the feedstocks and the process parameters, especially with cracking temperature and reactor residence time. These process parameters affect the 'severity' of the cracking process. 'High severity cracking', at higher temperatures and shorter residence times, needs more energy, but gives higher ethylene yields and lower propylene yields than 'low severity cracking'. Furthermore, the total share of valuable products is higher. During the last decades, new crackers have shifted to higher severity, although the increasing demand for propylene may be an incentive for lower severity cracking (Phylipsen *et al.*, 1995).

Because of the influence of severity and exact feedstock compositions on the output yields, in literature many different specifications are circulating. From those specifications it gets clear that not all of Europe's steamcrackers operate at high severity. Patel (1996) for example, who describes the German situation, mentions an average ethylene yield for naphtha cracking of about 23%, whereas Stratton *et al.*(1983) mention 30% and Chauvel *et al.*(1989a) 34%. Newly built plants show ethylene yields of about 35% (HCP, 1997). We take the yields specified by Stratton *et al.* (1983), which show modest severity, as a representative average for Western Europe in 1994. Modelled yields are given in Table 5.

Table 5 Average yields of steamcrackers in Western Europe

	Ethane[a] **[wt.%]**	**LPG[b,c]** **[wt.%]**	**Naphtha[a]** **[wt.%]**	**Gas oil[a]** **[wt.%]**
Ethylene	80	41	30	23
Propylene	2	17	16	14
C4	3	7	10	11
Pyrolysis gasoline (BTX)	1	7	23	20
Methane	7	25	15	8
Hydrogen	6	2	1	1
Pyrolysis fuel oil	0	1	4	22

[a](Stratton *et al.*, 1983); [b](Chauvel *et al.*, 1989a); [c]Calculated as mean between propane and butane cracking yields.

As described above, part of the output products of steamcrackers is valued as fuels. Part of these fuels is used internally for firing the cracking process. Remaining fuels can be exported and are thus considered as process outputs. We assume that the gaseous fuels (methane / hydrogen) are burned first, followed by the liquid fuels (pyrolysis fuel oil) if the process requires more energy than can be supplied by the gaseous fuels alone.

Energy requirement for steam cracking has shown a considerable decrease during the past decades. According to Steinmeyer (1997), energy requirement[6] for ethane cracking in up-to-date plants has decreased steadily from 35 GJ/tonne ethylene in 1955 to 12 GJ/tonne ethylene in 1990. For naphtha, gas oil and LPG steamcracking, similar declines of energy use may be supposed. However, an energy use of 12 GJ/tonne ethylene for ethane cracking seems to be too optimistic as an actual European average. According to Patel (1996) the average fuels use for ethane cracking in Germany in 1989 amounted to 16.5 GJ/tonne ethylene (Naphtha: 25.1 GJ/tonne ethylene, Gas oil: 30.3 GJ/tonne ethylene). New ethane cracking plants in 1997 show fuels requirements of 12.6 GJ/tonne (Stone & Webster, Linde), 13.0 GJ/tonne (KTI) and 13.8 GJ/tonne (Lummus) (HCP, 1997). We take the new plant with the highest fuels consumption (Lummus) as a representative for the Western European situation in 1994. In order to account for the existence of relatively old plants in Western Europe in 1994, we add 10% to its fuels requirement. So the average fuels consumption of ethane crackers in Western Europe in 1994 is calculated at 15.2 GJ/tonne. The same procedure is followed to calculate average fuels requirements for naphtha, LPG and gas oil cracking. The results are shown in Table 6.

In steamcrackers energy is needed for feedstock heating, for compression after cracking and for product separation. They contribute to the total energy requirement by about 65%, 15% and 20% respectively (Heijningen *et al.* 1992a). In the quenching and chilling steps high pressure steam is produced, the majority of which is used internally for compression and pumping. The alternative, compression and pumping with electrical compressors and pumps is less efficient. Although in 1994 there may still have been some crackers in Western Europe that do not use steam compressors and pumps, we assume that the average situation can be described by crackers that do. Because of this, electricity use is relatively low, 30 kWh, 40 kWh, 80 kWh and 100 kWh per tonne ethylene for ethane, LPG, naphtha and gas oil cracking respectively (Chauvel *et al.*, 1989a). According to Patel (1996) naphtha and gas oil cracking show a net production of high pressure steam of 0.9 GJ and 1.6 GJ per tonne ethylene respectively.

Material and energy balances for ethane, LPG, naphtha and gas oil steamcracking are shown in Table 6. They show that all processes, except ethane cracking, produce sufficient fuels to fulfil the energy demand of the process itself. For ethane cracking some extra fuel is needed. Table 6 also shows the CO_2 emissions due to internal combustion of self-produced fuels. They were calculated using the following CO_2 emission factors: methane: 2.74 kg/kg, hydrogen: 0 kg/kg and pyrolysis fuel oil: 3.35 kg/kg.

[6] Energy data for steamcrackers concern feedstock cracking including separation of the cracked products into ethylene, propylene, a C4 and a BTX fraction. Further separation of the C4 and BTX fractions into their components is excluded.

Table 6 Material and energy balances of steamcracking of ethane, LPG, naphtha and gas oil feedstocks; estimates for Western Europe. The figures are harmonised for the production of 1 tonne ethylene.

	Ethane		**LPG**		**Naphtha**		**Gas oil**	
	[t/t]	[GJ/t]	[t/t]	[GJ/t]	[t/t]	[GJ/t]	[t/t]	[GJ/t]
Inputs[a]:								
Feedstock	1.24	59.1	2.44	112.1	3.30	145.2	4.31	183.9
Outputs[a]:								
Products:								
Ethylene	**1.00**	47.2	**1.00**	47.2	**1.00**	47.2	**1.00**	47.2
Propylene	0.03	1.2	0.42	19.0	0.53	24.5	0.61	27.8
C4	0.04	1.8	0.18	8.1	0.33	15.2	0.48	21.8
Pyrolysis gasoline (BTX)	0.01	0.6	0.17	6.8	0.77	31.3	0.87	35.6
Total	**1.08**	**50.7**	**1.76**	**81.1**	**2.63**	**118.1**	**2.96**	**132.4**
Fuels:								
Methane	0.09	4.6	0.60	30.2	0.50	25.1	0.35	17.5
Hydrogen	0.07	8.7	0.05	5.7	0.03	4.0	0.04	5.2
Pyrolysis fuel oil	0.00	0.0	0.03	1.1	0.13	5.6	0.96	40.9
Total	**0.16**	**13.3**	**0.68**	**37.0**	**0.67**	**34.7**	**1.35**	**63.5**
Total output:	**1.24**	**64.0**	**2.44**	**118.2**	**3.30**	**152.8**	**4.31**	**195.9**
Process energy								
Electricity requirement[b,c]		0.11		0.29		0.29		0.36
Fuels requirement[d]		15.2		19.1		23.0		27.6
hp-Steam output[e]						0.9		1.6
Fuels remaining[f]:								
Methane	0	0	0.22	11.0	0.04	2.1	0	0
Hydrogen	0	0	0.05	5.7	0.03	4.0	0	0
Pyrolysis fuel oil	0	0	0.03	1.1	0.13	5.6	0.84	35.9
Total	**0**	**-1.9[h]**	**0.30**	**17.9**	**0.21**	**11.7**	**0.84**	**35.9**
CO_2 emissions[g]	0.25		1.05		1.26		1.35	

[a](Stratton *et al.*, 1983); [b][GJ_e]; [c](Chauvel *et al.*, 1989a); [d]Lummus cracker (HCP, 1997); 10% added in order to account for the existence of old plants; [e](Patel, 1996); [f]Calculated as: fuels output minus fuels requirement; [g]Only CO_2 emissions from internal combustion of produced fuels; [h]The negative value indicates that the process produces not enough fuels as by-products to fulfil its own energy requirement

4.3.2 Intermediates production

Part of the products of steamcracking can be used directly for the production of polymers. Ethylene is used as monomer for polyethylene and propylene as monomer for polypropylene. The C4 and BTX fractions, however need to be separated further before they can be used to produce polymers or other chemicals. From the C4 fraction, butadiene is extracted, which is needed for the production of Acrylnitril-Butadiene-Styrene (ABS). The BTX fraction is separated into benzene (used for the production of styrene and polyurethane (PUR)), toluene (used for PUR production) and xylenes, of which *p*-xylene is needed for the production of Polyethylene Therephtalate (PET). Other intermediates that are needed to produce polymers are styrene (used for the production of Polystyrene and ABS) and vinyl chlorine monomer (used to produce PVC).

Butadiene

The 1994 butadiene consumption in Western Europe amounted to 1500 ktonne (Zehnder, 1998). Butadiene is extracted from the C4 fraction of steamcrackers by extractive distillation. Chauvel *et al.* (1989a) describe five different butadiene extraction plants, using different solvents and different amounts of electricity (0.13-0.94 GJ_e per tonne butadiene) and steam (4.5-14.4 GJ per tonne butadiene). We use the mean value of the energy requirements of those five processes: 0.7 GJ_e electricity per tonne butadiene and 7.6 GJ steam per tonne butadiene as representative for Western Europe in 1994.

Benzene

Benzene consumption in Western Europe amounted to 6600 ktonne in 1994 (Zehnder, 1998). About half of the benzene is used for styrene production (Patel, 1996), (Zehnder, 1998). Benzene, toluene and xylenes can either be produced from the pyrolysis gasoline (BTX) fraction of steamcrackers or via catalytic reforming of naphtha, which also goes via a BTX fraction. According to Boustead (1993), about half of the benzene production goes via each route. In this study we investigate the production of benzene from the BTX fraction of steamcrackers.

Extraction of benzene, toluene or xylenes from a BTX fraction is rather difficult, because of the presence of aliphatic non-aromatic hydrocarbons, making simple distillation insufficient. Basically there are two routes to be followed. In the first route benzene, toluene and xylenes are obtained in three subsequent distillation steps, from which the aliphatic non-aromatic hydrocarbons are separated by extractive distillation. The second route works the other way round: first the aliphatic non-aromatic hydrocarbons are removed from the mixture by solvent extraction, after which benzene, toluene and xylenes are obtained in three subsequent distillation steps. In Germany the first route is used for 70% of benzene production (Patel, 1996). We assume that this is the major route for Western Europe and take it, therefore, as representative.

Boustead (1993) gives energy requirement figures that are valid for the average of Western European benzene production. His total energy requirement figure[7] corresponds to 2.9 GJ per tonne benzene. Patel (1996) mentions 2.0 GJ per tonne benzene, whereas Van Heijningen *et al.* (1992a) give a value of 10 GJ and Chauvel *et al.* (1989a) mention 2.1-3.9 GJ per tonne benzene, depending on the exact process and BTX fraction used. The value given by Van Heijningen *et al.* is certainly too high, because it is based on a very old source. The values given by Patel and Chauvel *et al.* refer to new, state-of-the-art plants. Because the data from

[7] Boustead's values are based on HHV. The given value was converted into LHV.

Boustead refer to the average Western European plant (including some rather old plants still existing in 1994), we use his figure for our calculations.

Toluene

According to Zehnder (1998), 2300 ktonne of toluene were produced in Western Europe in 1994. Because of a limited market for toluene, about half of it was converted into benzene and xylenes by hydrodealkylation (hydrodealkylation is not investigated in this study). The major share of toluene is produced from BTX by catalytic reforming. According to Chauvel *et al.* (1989a), 2.0 GJ steam and 0.02 GJ_e electricity per tonne toluene are needed for distillation. Chauvel does not give energy data for subsequent extractive dissolution, which is needed for the removal of aliphatic non-aromatic hydrocarbons. Because of the large similarity with benzene and xylene extractive distillation, we use the average values for these processes as an approach for toluene extractive distillation. With this, total energy requirement for toluene extraction is calculated at 3.7 GJ steam and 0.04 GJ_e electricity per tonne toluene.

p-Xylene

Western European production of xylenes in 1994 amounted to 2700 ktonne (Zehnder, 1998). These comprise *o*-xylene, *m*-xylene and *p*-xylene. For plastics production only *p*-xylene is needed. Therefore only the production of *p*-xylene is investigated in this study. *p*-Xylene production in Western Europe amounted to 1600 ktonne in 1994 (Zehnder, 1998). The production of *p*-xylene is more complicated than the production of benzene and toluene. After benzene and toluene have been distilled from the BTX fraction, all C_{9+} hydrocarbons are removed by distillation. The remainder is a mixture of xylenes, ethylbenzene and aliphatic non-aromatic hydrocarbons. The aliphatic non-aromatic hydrocarbons are removed by extractive distillation. Subsequently, ethylbenzene and *o*-xylene are removed in two distillation steps. After this, *p*-xylene is extracted by crystallisation. The remaining ‘mother liquor’, which has a high *m*-xylene content, is converted into *p*-xylene and *o*-xylene by isomerisation.

The complexity of xylenes production causes some complications in the investigation of the energy required for *p*-xylene production. The total process produces ethylbenzene, *o*- and *p*-xylene, as well as a C_{9+} fraction and a mixture of aliphatic non-aromatic hydrocarbons. Energy use for the ‘preparatory’ steps (C_{9+} distillation and aliphatic non-aromatic hydrocarbons extraction) is allocated to all products, based on mass proportions. Energy use for ethylbenzene and *o*-xylene distillation is entirely allocated to ethylbenzene and *o*-xylene respectively (and, therefore, play no role in the calculations). Energy use for crystallisation and isomerisation is allocated to *p*-xylene and *o*-xylene, based on mass proportions. Matreial flows are depicted in Figure 1.

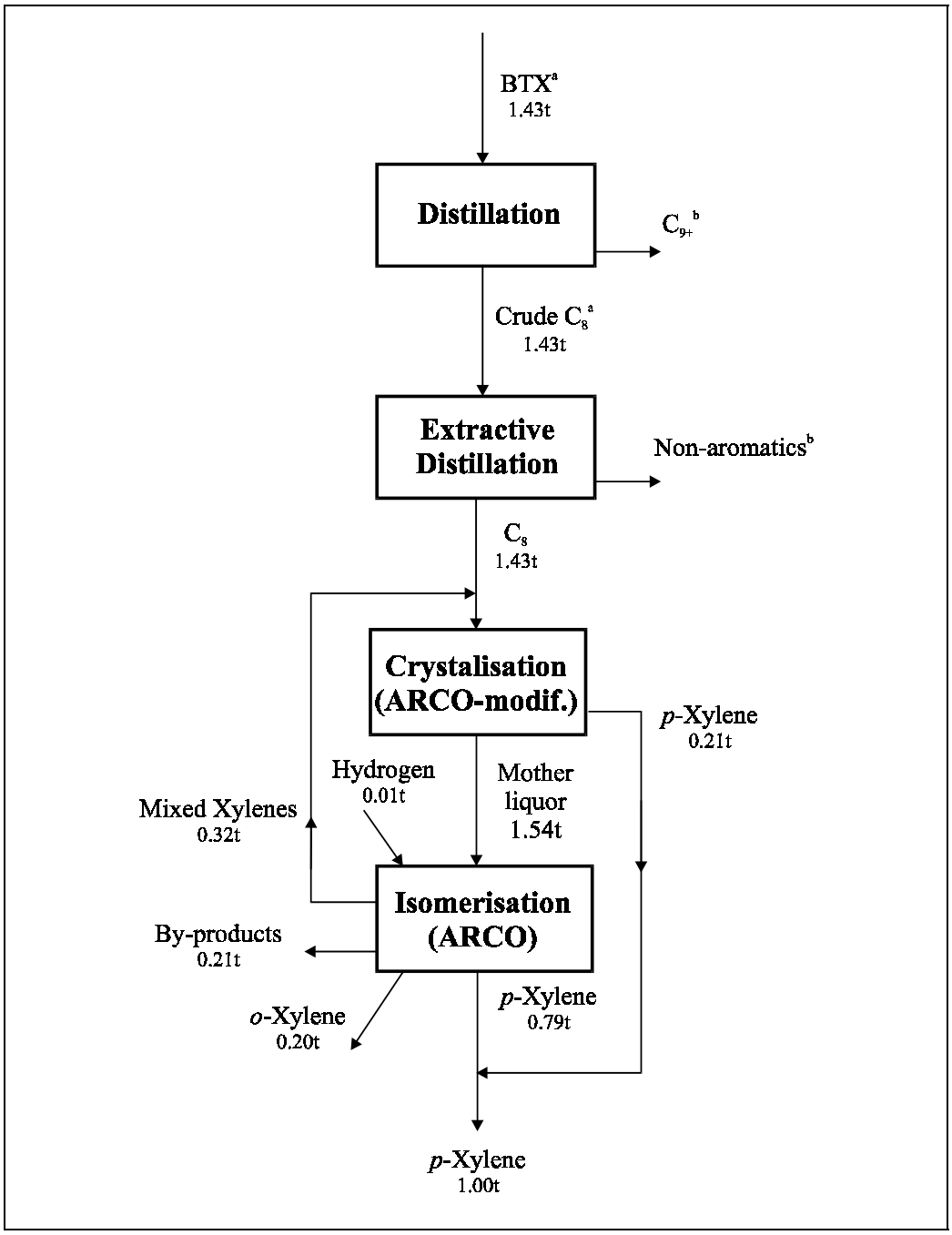

Figure 1 Process scheme of *p*-xylene production[8]. The distillation steps for ethylbenzene and *o*-xylene removal are not shown, because their energy use is entirely allocated to these two products. [a]In reality these flows are larger than 1.43 tonne. The indicated values only concern the part of BTX and Crude C_8 that is needed to produce 1 tonne of *p*-xylene; [b]Product mixes of distillation and extractive distillation depend on the composition of the BTX fraction used. Because the calculations only account for the part of the BTX that is converted into xylenes, these flows do not influence the calculations.

[8] The values indicated in this figure are material flows for coupled *p*-xylene and *o*-xylene production. For the calculations we use that part of the material flows that is involved in the production of *p*-xylene only. Therefore, values in Table 7 differ from values in Figure 1.

From energy data on the respective processes given by Chauvel *et al.* (1989a) we calculate the an electricity consumption of 1.0 GJ_e per tonne *p*-xylene, a steam consumption of 6.4 GJ/tonne and a gross fuels consumption of 5.9 GJ/tonne (see Table 7).

Table 7 Material and energy inputs and outputs of processes to produce the intermediates butadiene, benzene, toluene and *p*-xylene; estimates for Western Europe

	Unit	Butadiene	Benzene	Toluene	*p*-Xylene
Inputs:					
C4[a]	[t]	1.0			
BTX[a]	[t]		1.0	1.0	1.2
Hydrogen	[t]				0.01
Electricity	[GJ_e]	0.7	0.07	0.04	1.0
Steam	[GJ]	7.6	1.8	3.7	6.4
Fuel	[GJ]		1.0		5.9
Outputs:					
Butadiene	[t]	**1.0**			
Benzene	[t]		**1.0**		
Toluene	[t]			**1.0**	
p-Xylene	[t]				**1.0**
Aromatics	[t]				0.1
Fuel gas	[GJ]				4.0

[a] Only the part of the C4 and BTX that is converted to butadiene, benzene, toluene and *p*-xylene respectively is indicated.

Styrene

According to Zehnder (1998) in 1994 3100 ktonne of benzene were used in Western European to produce styrene. Because for each tonne of styrene 0.83 tonnes of benzene are needed (Chauvel *et al.*, 1989a), about 3700 ktonne of styrene were produced in 1994. Virtually all styrene is used for styrene polymers (PS: 65%, SBR: 14%, ABS: 7%, other polymers: 14% (Chauvel *et al.*, 1989a)). Nearly all styrene is manufactured by direct dehydrogenation of ethylbenzene. A negligible part of styrene is produced as co-product from ethylene oxide production. Nearly all ethylbenzene is obtained from ethylene and benzene via alkylation of benzene (Chauvel *et al.*, 1989a).

Input-output data on styrene production are derived from Chauvel *et al.* (1989a). For the alkylation step, 0.27 tonnes of ethylene and 0.75 tonnes of benzene are required per tonne ethylbenzene. Per tonne styrene between 1.10 and 1.16 tons of ethylbenzene are required

(depending on the reactor type). 30 to 50 kg toluene and 10 to 30 kg benzene are formed as by-products. Benzene is recycled to the alkylation step. For the combined process steps 0.31 tonnes of ethylene and 0.83 tonnes of benzene are required to produce 1 tonne of styrene. The process produces also a small amount of fuels, which is combusted to meet part of the process energy needs. Because these fuels consist mainly of hydrogen, CO_2 emissions from these fuels can be neglected.

Boustead (1993) gives energy requirement data that are the average of 20 Western European styrene plants. His data refer to net process energy requirement: the combusted fuels from the process itself are excluded. The dehydrogenation step produces also a considerable amount of lp- and hp-steam. According to Chauvel *et al.* (1989a), steam production is 0.6 – 2.25 tonne per tonne ethylbenzene, depending on the process used. From (HCP, 1995, 1997) a range of 1.5 – 2.6 tonne steam per tonne ethylbenzene can be derived. We use the average of the combined ranges as representative for Western Europe: 1.6 tonne steam per tonne ethylbenzene, corresponding to 1.8 tonne per tonne styrene, with an energy content of 4.8 GJ.

VCM

All of vinyl chloride monomer (VCM) produced is used to produce PVC (Rubin, 1990). Taking into account a material loss of 2% in PVC polymerisation, VCM use is calculated as 1.02 times PVC production. There are various ways to obtain VCM. In practice however, VCM is either produced from acetylene or from ethylene. Of the world VCM production capacity, 93% is based on the use of ethylene. Therefore we start from ethylene as feedstock. The production of VCM from ethylene runs via ethylene dichloride (EDC), which is either produced by chlorination or by oxychlorination of ethylene. EDC is cracked into VCM and hydrochloric acid (HCl). Chlorination and oxychlorination can be combined and balanced, so that only VCM is formed (see Figure 2). About one third of the world VCM production uses this balanced process. According to Van Heijningen *et al.* (1992a), energy use differs only marginally between different VCM production processes. We take the balanced process as representative for VCM production. Although it is possible to use either pure oxygen or air for oxychlorination, we only consider the use of pure oxygen, because air leads to the need for a considerably larger separation and purification unit with higher energy requirement and higher costs.

Energy data on the combined chlorination / oxychlorination process to produce VCM (Stauffer process) are given by Chauvel *et al.* (1989b), Van Heijningen *et al.* (1992a) and (Patel, 1996). The data of Chauvel and Patel are comparable (total final energy requirement 10.2 GJ and 9.9 GJ per tonne VCM respectively). The data of Van Heijningen *et al.* (6.1 GJ per tonne VCM) differs considerably. We take the data of Patel as representative.

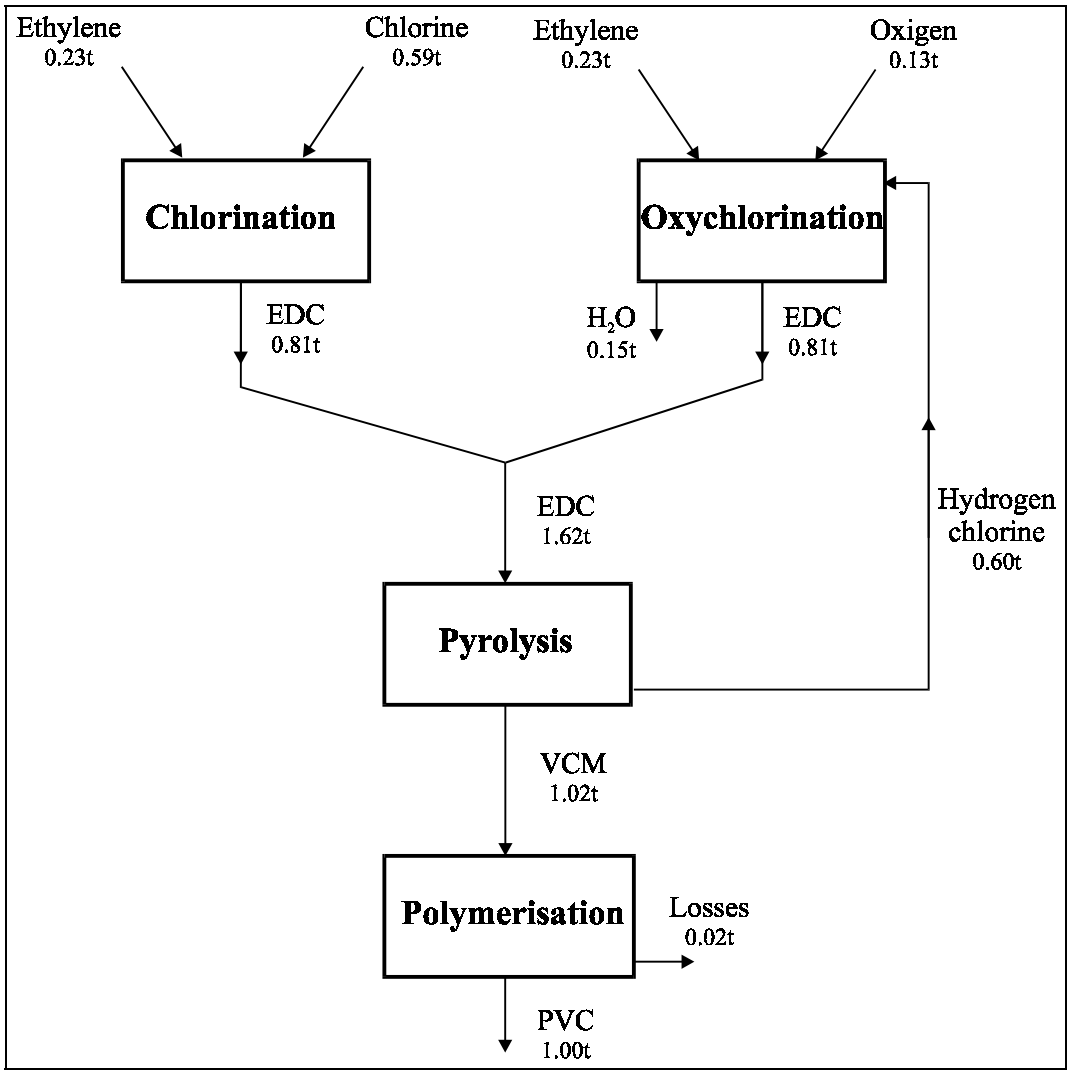

Figure 2 Process scheme of PVC production.

Data on the production of styrene and VCM are summarised in Table 8.

Table 8 Material and energy inputs and outputs of styrene and VCM production processes; estimates for Western Europe

	Unit	Styrene	VCM
Inputs:			
Ethylene	[t]	0.31	0.47
Benzene	[t]	0.83	
Chlorine	[t]		0.59
Oxygen	[t]		0.13
Electricity	[GJ_e]	0.3	0.3
Steam	[GJ]	5.1	5.3
Fuel	[GJ]	4.9	4.3
Natural gas	[GJ]		
Outputs:			
Styrene	[t]	**1.00**	
VCM	[t]		**1.00**
Toluene	[t]	0.04	
lp / mp-steam	[GJ]	4.8	

4.3.3 Polymers production

In Europe a lot of different polymer types and sub-types are produced. The most common types are Polyethylene (PE), Polypropylene (PP), PolyVinyl Chloride (PVC), Polystyrene (PS) and Polyethylene Therephtalate (PET). These so-called bulk plastics are widely applied in packaging, consumer goods and buildings. Apart from these bulk plastics, there are many speciality plastics, generally more expensive but with specific material properties. In our study the latter are collected into the categories ‘other thermoplastics’ and ‘thermosets’. The chief polymers of the category ‘other thermoplastics’ are Acrylnitril-Butadiene-Styrene (ABS) and polyamide (APME, 1996). We take ABS as a representative for this group. Of the group of thermosets, PUR is the most widely applied type (APME, 1996). Therefore we take PUR as a representative for the group of thermosets.

Table 9 summarises the production of plastics in Western Europe in 1994 (APME, 1996). Regarding Western Europe as a whole, import and export streams play no major role (Van Duin, 1997). Therefore, plastic production is treated as equivalent to plastic consumption.

Table 9 Western European plastics consumption in 1994 (APME, 1996) [ktonne]

Plastic type	Consumption
PE	9543
PP	4982
PS	2352
PVC	5401
PET	1971
Other thermoplastics	2807
Thermosets	5127
	35600

Six types of processes are used to produce polymers: liquid phase, gas phase, solution, suspension and emulsion polymerisation and polycondensation. With the liquid phase process (also referred to as bulk or mass polymerisation) the polymerisation takes place in liquid phase, at high pressure (LDPE: 1400-3500 bar) or low pressure (PP: 20-40 bar) and a temperature below 100°C. The gas phase polymerisation process (also called low-pressure polymerisation) is employed at low pressures (7-20 bar) and a temperature between 70 and 100°C. Both the liquid phase and the gas phase process run without the aid of a solvent. The solution polymerisation process uses a solvent (for example hexane) and runs at a pressure between 30 and 100 bar and a temperature between 150 and 250°C. The suspension polymerisation process (also referred to as the slurry process) is the oldest process. Like the solution process, it uses a solvent. The produced polymer is not soluble in the solvent, which leads to a suspension from which the polymer precipitates. The process takes place at a temperature below 110°C and a pressure below 40 bar. The emulsion polymerisation process is comparable to the suspension process, but is uses water as solvent, with emulsifiers and other additives to suspend the monomer and polymer. The polycondensation process is applied to produce PET, PUR and nylons. It takes place at higher temperatures (230-285°C). Unlike the polymerisation processes, which are exothermic, the polycondensation process is endothermic.

Energy requirements differ between the processes used. Because no solvent is used in the liquid phase and gas phase processes, only a simplified separation unit is needed, which requires less energy than the more extensive separation units of the solution, suspension and emulsion processes (EPA, 1997). Furthermore, the gas phase process generally consumes considerably less energy than the liquid phase process, because of the lower pressure applied.

Table 10 gives an overview of processes currently used to produce the different polymers.

Table 10 Typical polymerisation methods for the polymers discerned in this study (EPA, 1997), (Patel, 1996), (Van Heijningen *et al.*, 1992a,b). Processes that are applied most often are indicated with a rhombus (♦). Less frequently used processes are indicated with an x.

Plastic type	Polymerisation method				
	Liquid phase	Gas phase	Solution	Suspension / Emulsion[a]	Polycondensation
PE					
HDPE		x	x	♦	
LDPE	♦			x	
LLDPE	x	♦	x	x	
PP	♦	♦	x	♦	
PS	♦		x	♦	
PVC	x			♦	
PET					♦
ABS	x			♦	
PUR					♦

[a]Alternative process for PVC, PS and ABS polymerisation.

Currently, there is a shift in the direction of the production of metallocene polyethylene and polypropylene, using metallocene catalysts instead of conventional Ziegler-Natta catalysts. Metallocene catalysts allow better polymerisation control, leading to improved material quality. Patel (1996) expects that metallocene catalysts will replace about 30% of Ziegler-Natta catalysts over the next ten years. According to Seiler (1995) it is even possible that in about 10 years metallocene catalysts make up the major part of catalysts for polypropylene polymerisation. Optimism concerning the introduction of metallocene catalysts is widely shared (see for example (Van Stijn, 1996), (EPN, 1996) and (ECN, 1997)). Because metallocene catalysts can be used with the same polymerisation processes as the conventional Ziegler-Natta catalysts, there is no need to model them separately. Possible minor changes in energy use (due to changed process parameters) are neglected .

In the following paragraphs we successively discuss the polymerisation of PE, PP, PS, PVC, PET, ABS and PUR. Input materials are limited to the main building blocks of the plastics. Additives are not taken into account specifically.

Polyethylene (PE)

In 1994, 9543 ktonne of PE were consumed in Western Europe (APME, 1996) divided between High Density Polyethylene HDPE (3718 ktonne) and (linear) Low Density Polyethylene (L)LDPE (5825 ktonne). Of the latter fraction, about 75% was Low Density Polyethylene LDPE and 25% Linear Low Density Polyethylene LLDPE. During the last decade, especially LLDPE production has grown rapidly (6-7% p.a.), followed by HDPE (~3% p.a.), while LDPE production is hardly growing (0.5-1% p.a.) (Harzmann *et al.*, 1996), (Kaps *et al.*, 1996). The majority (76%) of LDPE and LLDPE is used to produce films

(Hartzmann *et al.*, 1996). The main applications of HDPE are blow moulded products (32%), injection moulded products (24%), films (19%) and tubes and plates (15%) (Kaps *et al.*, 1996).

LDPE can be produced from ethylene using the liquid phase or the suspension process (Table 10). Both in The Netherlands (Van Heijningen *et al.*, 1992a) and in Germany (Patel, 1996) the liquid phase process is the only one applied. LLDPE can be produced using the gas phase process, the solution process, the suspension process, or a modified form of the liquid phase process. In Germany, in 1989 the division was 60% / 20% / 20% / ~0% for these processes respectively. HDPE can be produced using the gas phase process, the solution process, or the suspension process. In Germany, in 1989 the division was 10% / 15% / 75% respectively (Patel, 1996). Because a substantial part of Western European polyethylene production takes place in Germany (about 25%: Patel, 1996) and for lack of better estimates we assume that the divisions of processes for polyethylene polymerisation for Western Europe as a whole (in 1994) are the same as the German process mixes (in 1989).

We discern five PE polymerisation options:

- LDPE liquid phase
- LLDPE gas phase
- LLDPE solution / suspension
- HDPE gas phase
- HDPE solution / suspension

Because of a relatively similarity between the solution and the suspension process, we model a combined solution / suspension process, the data of which can be seen as mean values for both processes.

Patel (1996) has carried out an extensive study on the energy requirement of the different polymerisation processes. We use his results as input data for our study. Input-ouput data and energy requirement can be read from Table 11. The material balance includes 20 kg. ethylene losses per tonne polyethylene. Because steam is both used and produced, steam figures represent net input (LLDPE / HDPE) or net output (LDPE).

Table 11 Material and energy inputs and outputs of PE polymerisation; estimates for Western Europe (based on Patel, 1996)

	unit	LDPE Liquid phase	LLDPE Gas phase	LLDPE Suspension / Solution	HDPE Gas phase	HDPE Suspension / Solution
Inputs:						
Ethylene	[t]	1.02	1.02	1.02	1.02	1.02
Electricity	[GJ_e]	3.1	2.0	1.7	2.0	1.7
Steam	[GJ]		0.3	1.6	0.3	2.0
Outputs:						
LDPE	[t]	**1.00**				
LLDPE	[t]		**1.00**	**1.00**		
HDPE	[t]				**1.00**	**1.00**
lp steam	[GJ]	0.4				

Polypropylene (PP)

Polypropylene consumption in Western Europe in 1994 amounted to 4982 ktonne (APME, 1996). Major markets for polypropylene are: packaging (36%, mainly films and injection moulded products), textiles and fibres (25%) and automotive applications (12.5%) (Beer, 1996)

Polypropylene is produced from propylene using a liquid phase, gas phase or suspension process (Van Heijningen *et al.*, 1992a), (Patel, 1996). In the Netherlands the division between these processes is 35% / 25% / 40% (Van Heijningen *et al.*, 1992a), in Germany 0% / 40% / 60% (Patel, 1996). Because the process mixes of The Netherlands and Germany differ considerably, it is not possible to deduce from them information on the likely Western European process mix. For lack of better estimates we assume that all three processes make up an equal share of polypropylene polymerisation in Western Europe.

Energy data are derived from Patel (1996), who surveyed the energy use for PP polymerisation using the three processes mentioned above. His results are summarised in Table 12, from which it can be seen that the gas phase process needs considerably less steam than the suspension process, whereas the steam requirement for the liquid phase process lies in between.

Table 12 Material and energy inputs and outputs of PP polymerisation; estimates for Western Europe

	unit	Liquid phase	Gas phase	Suspension
Inputs:				
Propylene	[t]	1.02	1.02	1.02
Electricity	[GJ_e]	2.1	2.1	2.1
Steam	[GJ]	1.2	0.8	1.8
Outputs:				
Polypropylene PP	[t]	**1.00**	**1.00**	**1.00**

Polystyrene (PS)

PS consumption in Western Europe in 1994 amounted to 2352 ktonne (APME, 1996). There are three types of PS: general purpose PS (GPPS), high impact or rubber modified PS (HIPS) and expanded PS (EPS). General purpose PS is crystalline and brittle. HIPS has a rubber (polybutylene) content of about 11%, whereas EPS is foamed with the aid of a blowing agent (pentane, ~8%). PS (excluding EPS) is used for injection moulded (60%) and extruded and thermoformed products (40%). Food packaging (40%) and consumer goods housings (25%) are the most important products made of PS (Wagner, 1996). EPS is mainly used for home insulation, road construction and packaging purposes.

PS is produced from styrene using a liquid phase, solution, suspension or emulsion process. The liquid phase process and the suspension process are used most extensively. It is, however, unknown which is the leading process. For this study we do not discern the three types of PS separately, but we model the Western European PS product mix as a whole. Of the three types of PS, general purpose PS covers the largest part. Therefore, the shares of polybutylene and pentane (4% and 2% respectively) in the total materials input for PS polymerisation are relatively small. For this reason we investigate the production of PS from styrene only, excluding the inputs of polybutylene and pentane. The deviation of the results caused by this simplification is expected to be negligible.

Energy data for the polymerisation of PS are given by Boustead (1993). He gives average values[9] for 20 Western European polymerisation plants, 10 of which produce GPPS, 7 produce HIPS and 3 EPS. Total final energy requirements (fuels + electricity + steam) derived from these data are 1.52 GJ per tonne GPPS, 1.54 GJ per tonne HIPS and 4.97 GJ per tonne

[9] Boustead's values are based on HHV, which were converted to LHV using the heating values from appendix A.

EPS[10]. Boustead also provides average energy requirement data for all PS polymerisation plants investigated. We do not use these averages (corresponding to a total final energy requirement of 2.0 GJ per tonne PS), because the product mix (GPPS / HIPS / EPS) produced by those 20 plants differs considerably from the actual total European PS polymerisation product mix. The share of EPS of the plants investigated by Boustead is only 14%, whereas the share of EPS in total Western European PS polymerisation is 26% (APME, 1996). We calculated the total average final energy requirement for PS polymerisation at 2.4 GJ per tonne PS produced. Energy requirements, as calculated, can be read from Table 13.

PolyVinyl Chloride (PVC)

PVC consumption in Western Europe in 1994 amounted to 5401 ktonne (APME, 1996). The main applications of PVC are pipes and conduits (48%) and front panels (15%) (Anonymous, 1997). PVC is used for building materials, because of its high weather resistance and consequently high lifetime. Depending on the PVC type (rigid / flexible), an additive content of up to 15% is not uncommon (BUWAL, 1996). An additive content of 10% is seen as a reliable average (Rubin, 1990). A wide range of additives is used. Taking all additives into account would lead to an extensive study by itself, which would be beyond the scope of this study. Therefore we confine ourselves to 'pure' PVC, with no additive content. Consequently, we take the energy use to produce pure PVC as an approximate of the energy use to produce additives.

PVC is polymerised from VCM using a suspension, emulsion, or liquid phase process. In Germany, PVC polymerisation is divided between these three processes as: 76% / 13% / 11% respectively (Patel, 1996). For the world as a whole the division is: 70% / 20% / 10% (Rubin, 1990). Energy data on PVC polymerisation can be found in (HCP, 1997), (Patel, 1996) and (Van Heijningen *et al.*, 1992a). Comparing the three different processes, it becomes obvious that the emulsion process requires considerably more energy (total final energy requirement: 8-10 GJ per tonne PVC) than the suspension process (2.6-6.5 GJ per tonne PVC), whereas the liquid phase process uses even less energy (1.2-2.3 GJ per tonne PVC). The latter can, however, not be used to produce all types of PVC that are needed, because it leads to PVC with inferior properties (Rubin, 1992). Based on energy data from Patel (1996), which are expected to be the most representative for the Western European situation in the mid-nineties, we calculated an average energy consumption for all PVC production processes of 4.5 GJ per tonne PVC. The modelled process parameters are given in Table 13.

[10] The difference between GPPS / HIPS on the one hand and EPS on the other hand are caused by the difference of the amount of steam required. Steam requirement for EPS polymerisation (1.67 tonne per tonne PS) is much higher than for GPPS and HIPS polymerisation (0.169 and 0.235 tonne per tonne PS respectively).

Polyethylene Therephtalate (PET)

Western European PET consumption is rapidly growing. In 1994, 1971 ktonne of PET were used, of which 1171 ktonne for fibres (APME, 1996). Of the remaining 800 ktonne, 88% was used to produce bottles (Anonymous, 1997). PET polymers are divided into amorphous and crystalline PET. Amorphous PET is suitable for films and fibres. For bottles crystalline PET is needed, which has better material properties than amorphous PET. Crystalline PET is produced from amorphous PET by adding an extra polymerisation step (Boustead, 1995). Because a large part of PET is used to produce bottles, we investigate the production of crystalline ('bottle-grade') PET. Consequently, the estimated energy consumptions per tonne of PET may be somewhat too high.

There are two routes to produce PET: via therephtalic acid (PTA) and via dimethyl therephtalate (DMT). In Germany, the DMT route is used for 90% of PET production (Patel *et al.*, 1998). In Western Europe, 65% of the PET production runs via the DMT route (Chauvel *et al.*, 1989b). According to Sattler (1981), energy consumption of both routes is comparable. Therefore, we analyse the DMT route. A process scheme is shown in Figure 3. For the polymerisation of PET, ethylene glycol and DMT are required. The production of ethylene glycol follows the following route: First ethylene is oxidised to ethylene oxide, which is subsequently hydrated to ethylene glycol. DMT is obtained by oxidation of *p*-xylene with methanol (Witten process). DMT and ethylene glycol are polymerised via polycondensation into PET. In the polycondensation step almost all methanol is recovered and recycled to the *p*-xylene oxidation step.

Energy data are calculated from data on the individual sub-processes from Chauvel *et al.*, (1989a,b), except for the production of DMT from *p*-xylene and methanol, for which specifications from HCP (1997) are used because of considerably lower energy requirement. We do not discuss all sub-processes separately, but present results for the whole process together, starting from *p*-xylene, ethylene, oxygen and small amounts of hydrogen, water and methanol and ending with 1 tonne of PET and some by-products, which are assumed to be not commercially attractive. The results are depicted in Table 13. Total final energy requirement of the whole process is calculated at 13.5 GJ per tonne PET. This value compares fairly to the value of 14.2 GJ per tonne PET as given by Patel *et al.* (1998) The oxidation of ethylene produces 0.23 tonne process CO_2 emissions per tonne PET (excluding CO_2 emission from fuels combustion).

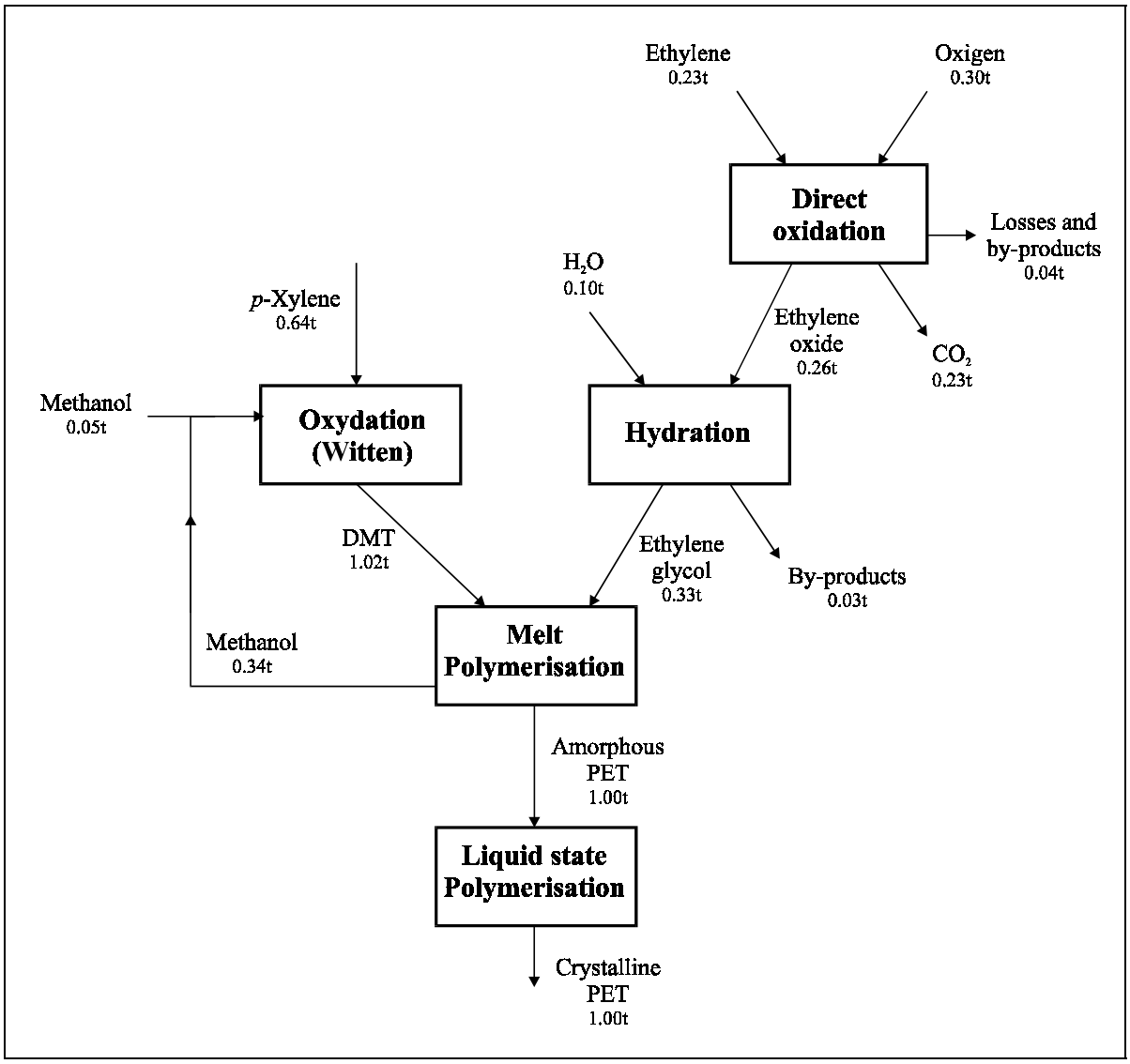

Figure 3 Process scheme of PET production

Other thermoplastics (ABS)

Western European consumption of other thermoplastics (ABS, SAN, PMMA, acetales, polycarbonates, polyamides, acrylics and others) amounted to 2807 ktonne in 1994 (APME, 1996). In this study the polymerisation of 'other thermoplastics' is modelled as Acrylonitril-Butadiene-Styrene (ABS) polymerisation. Western European ABS consumption amounted to 550 ktonne (including styrene-acrylonitril (SAN)) in 1994 (APME, 1996). ABS is mainly used to produce components for automotive, consumer electronics and refrigerators (88%) (Frohberg, 1996).

A process scheme of ABS production is shown in Figure 4. ABS is produced from acrylonitril, butadiene and styrene. ABS polymerisation can be carried out using a liquid

phase, suspension or emulsion process. Emulsion polymerisation is the world most applied process (Van Heijningen *et al.*, 1992b) and is therefore chosen as a representative for Western European ABS production. It consists of two steps: first butadiene is polymerised to polybutadiene, to which acrylonitril and styrene are added to form the ABS polymer. The shares of acrylonitril, butadiene and styrene can be varied within wide ranges. According to Van Heijningen *et al.* (1992b), the composition: acrylonitril: 25%, butadiene: 20%, styrene: 55% can be seen as representative average composition. Therefore this composition is used in our analysis. Acrylonitril is produced from ammonia, propylene and oxygen using the Sohio process, which is used for 90% of the world ABS production capacity. The raw material for this process, ammonia is produced by steam reforming of natural gas. In our study ammonia production is considered as auxiliary material (see paragraph 4.3.6).

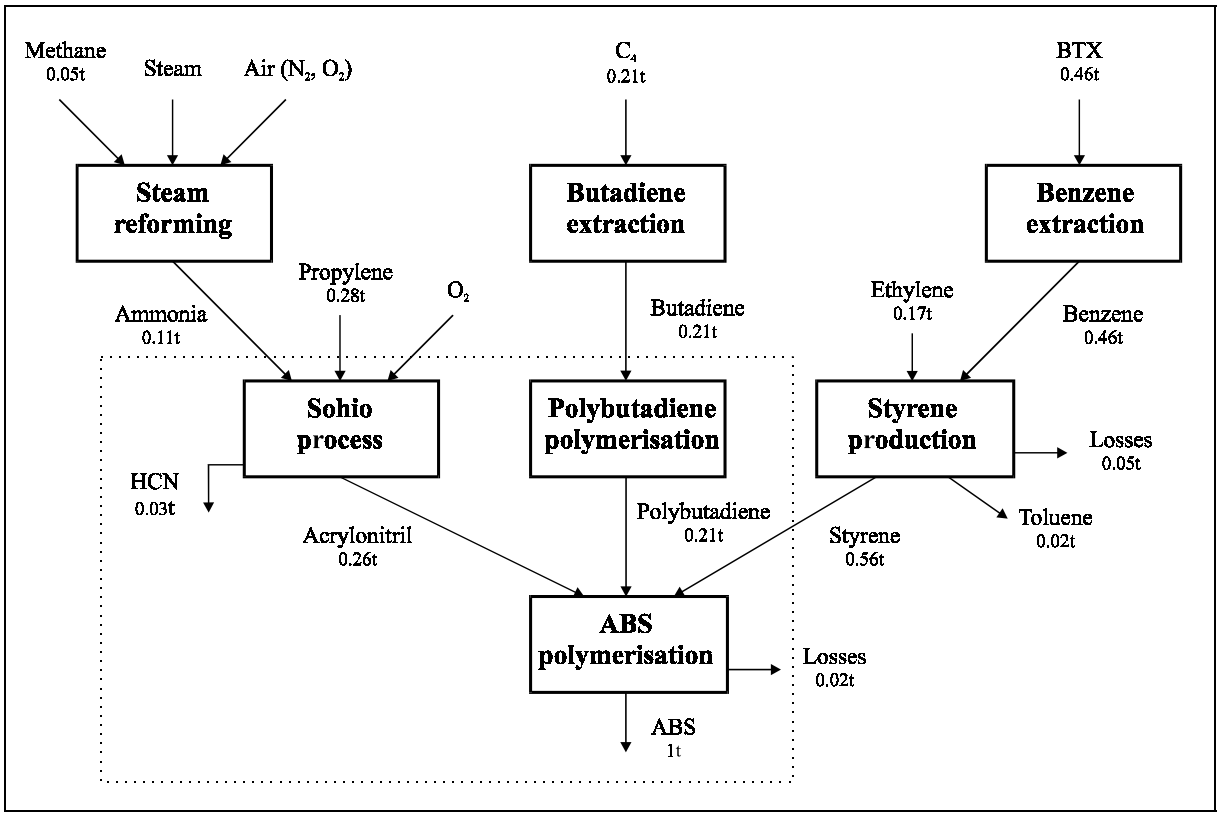

Figure 4 Process scheme of ABS production. System boundaries for the analysis of ABS production are indicated by dotted lines. Butadiene extraction, benzene extraction and styrene production are discussed in paragraph 4.3.2; ammonia and oxygen production are discussed in paragraph 4.3.6.

Energy data are estimated on the basis of acrylonitril production from Van Heijningen *et al.* (1992b), and our own estimate of energy needed for ABS polymerisation, based on comparable PS and PVC suspension / emulsion polymerisation processes. This wat we estimate the following energy consumption values: electricity: 1.8 GJ_e per tonne, steam: 1.2 GJ per tonne, natural gas: 0.4 GJ per tonne and fuel: 0.5 GJ per tonne.

The production of acrylonitril has a number of by-products. Apart from HCN, these offgasses and heavy fractions are regarded as fuels (1.6 GJ per tonne ABS) (Van Heijningen *et al.*, 1992b).

Process data is summarised in Table 13.

Thermosets (PUR)

Western European consumption of thermosets in 1994 amounted to 5127 ktonne (APME, 1996). The main thermosets are amino resins (35%), and polyurethanes (PUR: 34%) (APME, 1996). In this paragraph we discuss the production of polyurethane (PUR), which is taken as representative for the whole group of thermosets. In 1994, PUR consumption in Western Europe amounted to 1720 ktonne (APME, 1996). There are four types of PUR: rigid foams, soft foams, elastomers and coatings.

The production of PUR is based on the polyaddition of polyether-polyols and diisocyanates. Two polyether-polyols are used in PUR production: one produced from ethylene oxide and one produced from propylene oxide. According to Patel *et al*. (1998) they make up 39% and 61% respectively of German PUR production. We assume that these percentages are representative for Western Europe as a whole. Also two types of diisocyanates are used: tolylene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI). The route via TDI (mainly to produce flexible foams) and the route via MDI (mainly to produce rigid foams) each make up about half of PUR production capacity (Patel *et al.*, 1998). Both routes require different shares of polyether-polyols and diisocyanates. The TDI route requires 71% polyether-polyols and 29% TDI, whereas the MDI route requires 39% polyether-polyols and 61% MDI (Patel *et al.*, 1998). With these percentages an overall process scheme is constructed, as is presented in Figure 5. In this scheme mean material requirements for the production of 1 tonne of PUR are indicated. Blowing agents, used to produce PUR foam, make out a small part of materials use and are therefore not considered in this study.

The production of TDI includes the following steps: (1) nitration of toluene with nitric acid to dinitrotoluenes, (2) reduction of dinitrotoluenes to tolylene diamine (TDA) and (3) phosgenation of tolylene diamine to tolylene diisocyanate (TDI). The production of MDI also contains three steps: (1) nitration of benzene with nitric acid to nitrobenzene, (2) reduction of nitrobenzene to aniline and (3) phosgenation of aniline to diphenylmethane diisocyanate (MDI). For each step a number of process variants is available. We do not, however, discuss each sub-process in detail, but present overall values concerning the whole process. Energy requirement for the whole process is calculated from data on the individual sub-processes from (Chauvel *et al.*, 1989b), except for the polycondensation step, for which the energy

requirement is treated as equal to the energy requirement for PET polycondensation. Chauvel's data concern plants built in 1986, which we assume to be a good average for the plants in 1994.

Figure 5 shows that a number of by-products is produced. However, most by-products are produced in relatively small amounts. We assume that they are not commercially interesting, except for hydrochloric acid, which is produced in relatively large amounts (0.32 tonnes per tonne PUR) and which can be sold. So the processes to produce TDI and MDI respectively are regarded as combined TDI / hydrochloric acid and MDI / hydrochloric acid production processes. Materials and energy needed for these processes are partly used to produce TDI or MDI and partly to produce hydrochloric acid. We allocated the materials and energy needed for the process between the joined products based on their relative shares (on mass basis).

Using the material flows of Figure 5, the final energy requirement for the total process is calculated at 18.2 GJ per tonne PUR. Patel *et al.* (1998) give a lower value: 15.9 GJ per tonne PUR. The main reason for this difference is the fact that the production of propylene oxide is not included fully in Patel's value. Propylene oxide production is a highly energy consuming process. Direct oxidation of propylene is not commercially feasible. Therefore, in Western Europe, the chlorohydrin process is used to produce 82% of propylene oxide (Weissermel *et al.*, 1994). In this process propylene oxide is produced from propylene, sodium chloride and water. It includes an electrolysis step, which is highly energy consuming. According to Chauvel *et al.* (1989b) the production of propylene oxide uses 28.7 GJ of final energy per tonne propylene oxide. This is in contrast to the production of ethylene oxide, which can be obtained by direct oxidation. This exothermic process uses 1.8 GJ_e electricity per tonne ethylene oxide and delivers 4.0 GJ of steam per tonne ethylene oxide, which can be used in the other processes for PUR production.

The data on material and energy inputs and outputs of polymers production processes are summarised in Table 13.

Table 13 Material and energy inputs and outputs of PS, PVC, PET, ABS and PUR production[a]; estimates for Western Europe

	unit	PS	PVC	PET	Other thermoplastics (ABS)	Thermosets (PUR)[b]
Inputs:						
Ethylene	[t]			0.23		0.19
Propylene	[t]				0.28	0.30
Butadiene	[t]				0.21	
Benzene	[t]					0.13
Toluene	[t]					0.05
p-Xylene	[t]			0.64		
Styrene	[t]	1.02			0.56	
VCM	[t]		1.02			
Hydrogen	[t]					0.02
Methanol	[t]			0.05		
Oxygen	[t]			0.30	[c]	0.25
Ammonia	[t]				0.11	
Chlorine	[t]					0.20
Sodium chloride	[t]					0.06
Formaldehyde (37% wt.)	[t]					0.08
Nitric acid	[t]					0.18
Carbon monoxide	[t]					0.09
Electricity	[GJ_e]	0.7	1.0	2.5	1.8	8.6
Steam	[GJ]	1.5	2.8	4.2	1.2	11.3
Natural gas	[GJ]			3.1	0.4	
Fuel	[GJ]	0.2	0.7	3.8	0.5	
Outputs:						
PS	[t]	**1.00**				
PVC	[t]		**1.00**			
PET	[t]			**1.00**		
ABS	[t]				**1.00**	
PUR	[t]					**1.00**
Di-ethylene glycol	[t]			0.03		
Tri-ethylene glycol	[t]			0.00		
HCN	[t]				0.03	
Process CO_2 emissions	[t]			0.23		0.19
Fuels	[GJ]				1.6	1.7

[a]Inputs and outputs that are not used in the calculations (for example inputs and outputs of H_2O) are not shown; [b]The values in this column differ from the values given in Figure 5, because Figure 5 concerns the combined production of PUR and Hydrochloric Acid (as by-product of MDI production), whereas this table gives values allocated to PUR production only; [c]Neglected

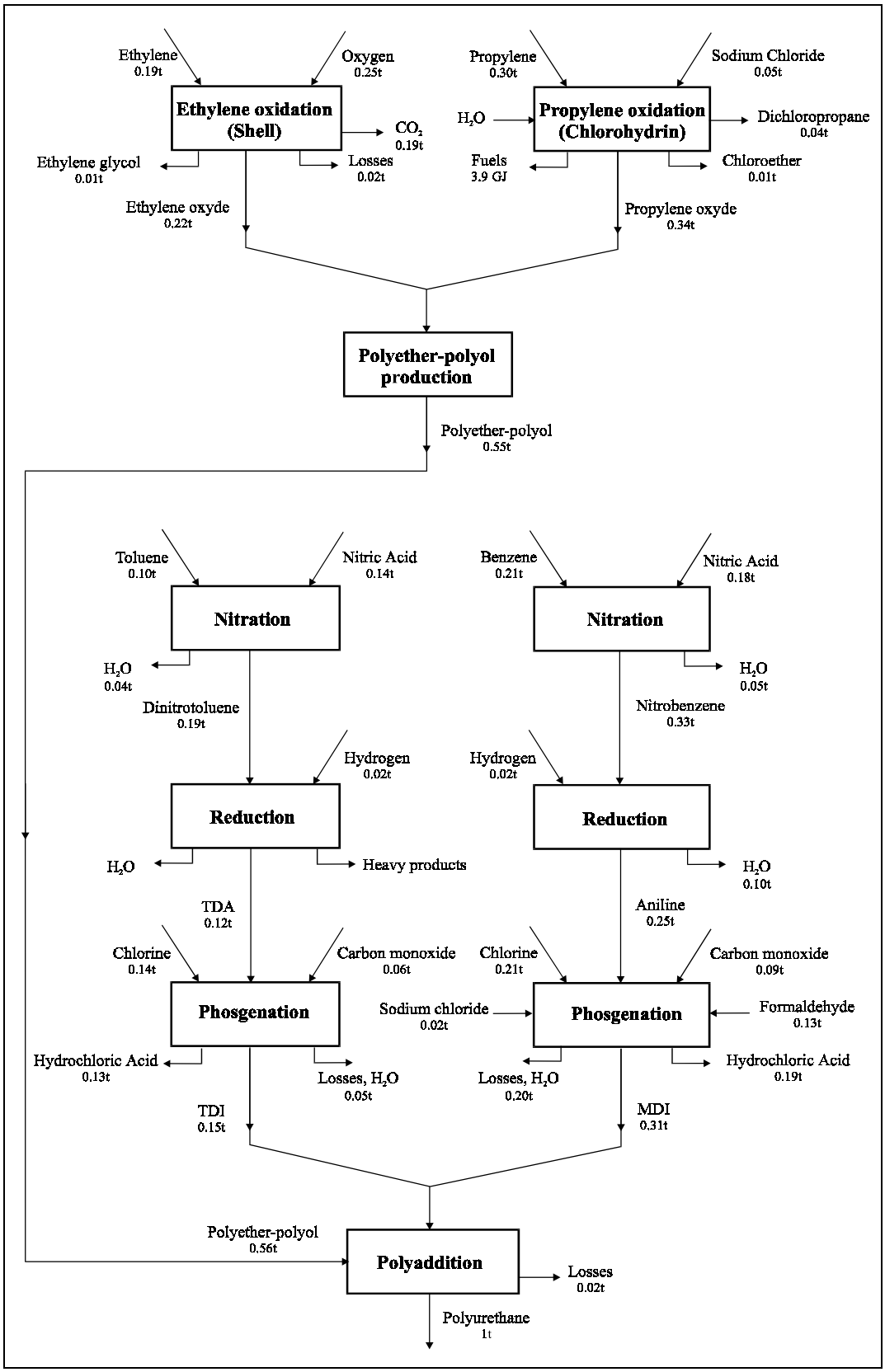

Figure 5 Process scheme of PUR production. The production of the input materials is discussed in paragraphs 4.3.1, 4.3.2 and 4.3.6.

4.3.4 Plastic processing

Polymers are transformed into plastic products using a variety of processes. Table 14 specifies the main plastic processing routes together with their relative importance from a quantitative point of view.

Table 14 Western European plastic consumption 1994, subdivided by processing routes (APME, 1996)

	Plastic consumption [ktonne]	**Share**
Film extrusion	6694	25%
Extrusion coating	638	2%
Sheets extrusion	283	1%
Thermoforming	1219	5%
Blow moulding	2456	9%
Injection moulding	4698	18%
Foaming	1980	8%
Tubes extrusion	2289	9%
Profiles extrusion	1090	4%
Cables extrusion	747	3%
Other processes	4162	16%
Total	**26256**	**100%**

The process that is applied to manufacture a plastic product is strongly connected to the shape of the product. Novem, the Netherlands Agency for Energy and the Environment, have published energy data on plastic processing routes (Novem, 1997). Their energy requirement values concern the situation in The Netherlands[11], which we assume to be comparable to the situation in Western Europe. Energy requirements for the different processes can be found in Table 15. These are average values for each plastic processing route. In practice energy use per tonne product is highly depending on product shape and dimensions, plastic type and machine configuration. For example, electricity use for injection moulding varies between 3.2 and 7.2 GJ_e/tonne product (Novem, 1997). For producing small products, more energy is needed (per ton) than for producing larger products. For our calculations we use the mean values presented in Table 15.

[11] If the total electricity use in the plastics processing industry in The Netherlands is calculated using the electricity requirements in Table 15, reasonable correspondence is found with national statistics: 938 million kWh (calculated) versus 996 million kWh (CBS, 1992), (Eijssen *et al.*, 1993).

Table 15 Energy use of plastic processing routes (Novem, 1997); estimates for Western Europe

	Electricity [GJ_e/tonne]	**Natural Gas** [GJ/tonne]
Film extrusion	1.9	
Extrusion coating	1.9	
Sheets extrusion	1.8	
Thermoforming	12.6	
Blow moulding	2.2	
Injection moulding	5.2	
Foaming	0.4	1.0
Tubes extrusion	1.4	
Profiles extrusion	1.4	
Cables extrusion	1.8	
Other processes[a]	3.7	0.1

[a] Mean value of the other processes in this table

According to the APME (1996) 1838 ktonne of plastic wastes were produced by Western European plastic processors in 1994. This is 7% of the plastics used in this industry. Therefore, 1.07 tonne of plastics are assumed to be needed to produce 1 tonne of plastic products.

4.3.5 Plastic waste management

In this paragraph processes for plastic waste management are investigated. Two types of plastic waste are discerned: post consumer waste, consisting of all plastic waste from discarding used products (by households and industries) and industrial plastic waste, arising from the production of plastic products. In 1994, 17505 ktonne of post consumer plastic waste were produced in Western Europe, as well as 1838 ktonne of industrial plastic waste (APME, 1996). The largest part (77%) of post consumer plastic waste was disposed of by landfilling. The shares of the other waste management processes: incineration with or without heat recovery, mechanical recycling and back-to-feedstock recycling are shown in Table 16. Almost all industrial plastic waste (95%) was processed via mechanical recycling (APME, 1996).

Table 16 Western European plastic waste management in 1994 (APME, 1996))

	[ktonne]
Post-consumer plastic waste	**17505**
Landfilling	13488
Incineration without heat recovery	561
Incineration with heat recovery	2348
Mechanical recycling of post consumer plastic waste	1057
Back To Feedstock recycling[a]	51
Industrial plastic waste	**1838**
Mechanical recycling of industrial plastic waste	1746

[a]Pyrolysis, gasification, hydrogenation, blast furnace injection

Depending on the condition of the material, three qualities of plastic waste can be discerned:
- Unmixed plastic waste (‘high quality’)
- Mixed plastic waste (‘medium quality’)
- Mixed plastic waste in municipal solid waste (‘low quality’)

Unmixed plastic waste consists of only one plastic type. Industrial plastic waste from the plastics processing industry mostly fulfils this condition. Another example of unmixed plastic waste is formed by multiple use packaging, which is returned to the producer and is released in large, sorted quantities. *Mixed plastic waste* is, for example, obtained by separate collection of plastic packaging waste, *e.g.* the ‘Duales System Deutschland’ (DSD) in Germany. The waste stream obtained this way contains all types of plastics mixed. Although the waste stream contains some remnants of food and other dirt, it is far less contaminated than the third type: *mixed plastic waste in household waste*, which is obtained if plastic waste is not collected separately and which is mixed with all kinds of other waste materials.

Plastic processing techniques make specific minimum demands on the quality of the plastic waste to be handled. These qualities roughly correspond to the three types of plastic waste discussed above.

Processes that are suited to plastic waste of all qualities are:
- Disposal (‘landfilling’)
- Incineration without heat recovery
- Incineration with heat recovery

Processes that require at least ‘medium quality’ plastic waste are:
- Plastic waste injection in blast furnaces, in which plastics serve as reducing agent
- Pyrolysis, heating in absence of oxygen
- Gasification, heating in the presence of a controlled amount of oxygen

- Hydrogenation, gasification in the presence of hydrogen

Processes that require at least 'high quality' plastic waste are:
- Mechanical recycling ('re-extrusion')
- Chemical recycling (methanolysis, glycolysis, hydrolysis *etc.* of polycondensation polymers (PET, PUR, PC, nylon))

'Low quality' plastic waste can be upgraded to 'medium quality' plastic waste by separating plastics from other waste components. Upgrading of 'medium quality' plastic waste to 'high quality' plastic waste is practically impossible, because of the huge range of intermingled plastic types and sub-types.

All plastic waste management processes, except 'disposal' and 'incineration without heat recovery' aim at obtaining specific usable 'products' from the waste stream. These usable 'products' may be energy and / or materials that can either be used to produce new plastic products or serve as feedstocks for the petrochemical industry.

Processing routes for mixed plastic waste in municipal solid waste

Plastic waste in municipal solid waste is heavily contaminated and intermingled with all kind of other waste materials. Material recycling is only possible after extensive sorting, which is generally not yet economically feasible. Processing routes for mixed plastic waste in municipal solid waste only make use of (a part of) the *energy* content of the waste plastics, if at all. We give a short description of the processes for processing mixed plastic waste in municipal solid waste and focus on the amount of energy that is recovered and the process CO_2 emissions involved. We do not discuss plastic waste *collection*. According to Van Heijningen (1992b) the energy use of waste collection is limited to 0.1-0.2 GJ fuel per tonne waste. Therefore, the energy use for waste collection and the CO_2 emissions involved are neglected in this study.

Landfilling

Landfilling is the easiest method to dispose of waste. However, no use is made of the energy and material contents of the waste materials and large areas of land are needed for waste storage. Therefore, governments of a number of European countries (for example The Netherlands and Germany) reduce landfilling with legislative prohibition of disposal of waste that can be processed otherwise.

Energy requirement for landfilling is relatively low. According to Faaij (1998), 0.14 GJ fuel oil per tonne waste is needed for soil displacements. Because the rate of decay of plastics is negligible, no process CO_2 emissions are involved in disposal.

Incineration

Incineration is a means to reuse part of the energy content of waste, which is converted into electricity. However, a small part of the waste combustion installations in Europe does not make use of the energy that is released (see Table 16). According to Patel *et al* (1998), plastic waste has a mean lower heating value (LHV) of 38.2 GJ per tonne. The mean energy conversion efficiency of waste incineration plants in Western Europe is estimated at 20% in 1994 (Gielen *et al.*, 1994). This means that per tonne of plastic waste 7.6 GJ_e electricity is produced. The remaining energy is released as low quality heat that could, in principle, be used in district heating or industry. In 1994, however, hardly any use was made of this heat.

CO_2 emissions from combustion depend on the plastic type that is incinerated. Table 17 gives an overview of the CO_2 emission factors of combustion of the different plastic types as calculated from the combustion reaction equations. In our calculations we use for mixed plastic waste combustion the –average– CO_2 emission factor of 2.88 tonne CO_2 per tonne plastic waste (Patel *et al.*, 1998).

Table 17 Post consumer plastic waste composition (APME, 1996), CO_2 emission factors of plastics incineration, calculated from the combustion reaction equations

	Waste composition [%]	**CO_2 emission factor** [t/t]
PE	43.8	3.14
PP	15.8	3.14
PS	9.0	3.38
PVC	12.1	1.42
PET	4.1	2.29
ABS	1.9	3.13
PUR	3.3	2.59
Others	10.0	2.88
Mixed plastic waste		*2.88*

Upgrading to 'mixed plastic waste'

'Mixed plastic waste in municipal waste' can be upgraded to 'mixed plastic waste', using a series of sorting and separation processes. According to Patel *et al.* (1998), electricity use involved in these processes amounts to approximately 1.1 GJ_e per tonne separated plastic waste. This figure refers to the German DSD, in which five plastic fractions are obtained from mixed packaging waste. Sas *et al.* (1994) calculate an electricity use of 0.4 GJ_e per tonne plastic waste, as well as a natural gas use of 0.9 GJ per tonne plastic waste. Their figures are

based on an experimental waste sorting installation. Sas *et al.* (1994) give an uncertainty margin of ±30%, caused by the experimental character of the installation. For our calculations we assume an electricity use of 0.3 GJ per tonne plastic waste and a natural gas use of 0.8 GJ per tonne plastic waste.

Processing mixed plastic waste

Mixed plastic waste can be used for Back-To-Feedstock (BTF) recycling. With BTF recycling processes mixed plastic waste is converted into feedstocks that can be used in the petrochemical industry to produce new plastics or other petrochemical products. In 1994 four BTF recycling processes were available: plastic waste injection in blast furnaces, pyrolysis, gasification and hydrogenation. These processes were only used in Germany (APME, 1996). The 'Duales System Deutschland' (DSD) aims at recycling all packaging waste, calling for large recycling facilities. Because of this, feedstock recycling in Germany is growing rapidly: 15 ktonne in 1993, 51 ktonne in 1994 (APME, 1996), 99 ktonne in 1995 and 251 ktonne in 1996 (Patel *et al.*, 1998). For the calculations we used the 1994 value: 51 ktonne.

Before plastic waste is suitable for BTF recycling, preparatory treatment is needed, consisting of grinding, separation of non-plastics, sieving, washing, drying and granulation. For these processes about 0.8 GJ_e electricity is needed per tonne mixed plastic waste (Patel *et al.*, 1998).

Plastic waste injection in blast furnaces

Plastic waste is injected in blast furnaces to serve as reduction agent to absorb oxygen from iron ore to produce iron. Normally, heavy oil is used for this purpose. By injecting plastic waste, part of the heavy oil is saved. At most 30% of heavy oil can be substituted 1:1 by plastic waste (Patel *et al.*, 1998). It is disputable whether the process should be regarded as material recycling or as a form of incineration. Because heavy oil or plastic waste injection in blast furnaces does not primarily aim at combustion for energy production, but to obtain a chemical reaction in which the reduction agent is materially involved, we do consider this process as material recycling. This is also the view of the DSD in Germany, which allows plastic waste injection in blast furnaces by virtue of the process's material recycling properties. We model plastic waste injection in blast furnaces as a 'dummy' process that converts mixed plastic waste, without energy requirement and without costs (except for the preparatory treatment discussed above), into heavy oil, that can subsequently be used as reduction agent in blast furnaces.

Pyrolysis

Heating plastic waste in absence of oxygen in fluidised bed reactors causes polymers to fall apart into smaller molecules. This process is called 'pyrolysis'. Kaminsky *et al.* have studied

this process in detail since the seventies, at various temperatures (600-800ºC), for various waste compositions, with and without the use of steam. Despite large research efforts (for example Kaminsky *et al*., 1992, 1992b, 1995, 1995b, 1996, Kastner *et al.*, 1995, Simon *et al.*, 1996, Kim *et al.*, 1997), only a demonstration plant of 5 ktonne capacity has been built in Ebenhausen, Germany, which was closed in 1989 for insufficient cost-effectiveness. A 50 ktonne plant is planned to be built in Leuna, Germany.

BASF follows another approach. The BASF pyrolysis process takes place at relatively low temperatures (400ºC). In 1994, a 15 ktonne pilot plant was built, with the intention to build a 300 ktonne plant, which would be capable of processing more than half of the German plastic packaging waste. However, because the DSD could not guarantee such a large amount of plastic waste to be delivered annually, the plant has never been built and the pilot plant was closed in 1996.

For our calculations we use data from (Patel *et al.*, 1998) on the BASF pyrolysis process. From the fact that BASF recently intended to build a large plant we conclude that this process is probably the most cost-effective one. Products are naphtha, BTX, pyrolysis gas and petcokes. The first two are considered as products, the latter two as fuels. Data on this process can be read from Table 19.

Gasification

Gasification is obtained if plastic waste is heated to temperatures of 800-1300ºC in the presence of controlled amounts of steam and oxygen. This way plastic waste disintegrates into synthesis gas, which consists of carbon monoxide and hydrogen. Synthesis gas can be used to produce various hydrocarbons (Aurich, 1994) or hydrogen. Patel *et al.* (1998) have investigated gasification with joint methanol synthesis. For this study we have investigated the production of hydrogen. Gasification is followed by a shift reaction in which carbon monoxide reacts with steam to hydrogen and carbon dioxide. Consequently, in this approach plastic waste is converted into hydrogen and carbon dioxide. Table 18 shows the inputs and outputs of gasification with coupled hydrogen production from several plastic types (Gielen *et al.*, 1994). Table 18 also shows calculated input and output figures for gasification of mixed plastic waste equivalent to the European overall post user plastic waste composition in 1994 (APME, 1996). Data on gasification are collected in Table 19.

Table 18 Inputs and outputs of plastic waste gasification (with coupled hydrogen production) for several plastic types (Gielen *et al.*, 1994) and calculated values for mixed plastic waste gasification

			Polyolefins	**PS**	**PVC**	**Other plastics**	**Mixed plastic waste**
	MPW composition[a]		60%	9%	12%	19%	
IN:	Plastic waste	[t]	1	1	1	1	**1**
	Oxygen[c]	[t]	1.1	1.2	0.5	1.0	**1.1**
	Natural gas	[GJ]	3.8	2.6	1.7	2.9	**3.3**
	Electricity	[GJ_e]			0.7		**0.08**
	Na(OH)	[t]			0.65		**0.08**
OUT:	Hydrogen	[t]	0.29	0.22	0.1	0.17	**0.24**
	Electricity	[GJ_e]	0.3	0.1			**0.19**
	Process CO_2 emissions[b,c]	[t]	3.14	3.35	1.3	2.3	**2.77**

[a](APME, 1996); [b]Process emissions (excluding emissions from fuels combustion); [c]Calculated from the reaction equations

Hydrogenation

Plastic waste can be hydrogenated with hydrogen to form 'syncrude' (synthetic crude oil: comparable to naphtha) that can serve as an alternative for naphtha in steamcracking, together with e-gas (energetic gas: comparable to natural gas) that can be used as fuel and a hydrogenation residue that can also be used as fuel (Saykowski *et al.*, 1994). The process is exploited by VEBA oil in a plant in Bottrop (Germany), which processed 28 ktonne plastic waste in 1995. In this plant, mixed plastic waste is hydrogenated together with the vacuum residue from crude oil distillation. Plastic waste has a share of about 25%.

The process consists of two steps: first mixed plastic waste is cracked and separated into a heavy fraction (30%) and a light fraction (70%). The light fraction is processed in a hydrotreater into syncrude and e-gas. The heavy fraction is mixed with Vacuum Residue and led to a VCC (Veba Combi Cracker). Here it is hydrogenated under high pressure (~300 bar), at a temperature of about 470ºC. The outputs are syncrude, e-gas and a hydrogenation residue. The above shows that the processing of mixed plastic waste and vacuum residue in the hydrogenation process are coupled. Processing of vacuum residue, however, is no part of the plastics lifecycle. Therefore, the energy used to process the vacuum residue is subtracted from total energy use, in order to obtain the energy used to process plastic waste only.

Table 19 Material and energy inputs and outputs of processes for processing mixed plastic waste

	unit	Blast furnace Injection[a]	Pyrolysis[b]	Gasification[c]	Hydrogenation[d]
Inputs:					
Mixed plastic waste	**[t]**	**1.00**	**1.00**	**1.00**	**1.00**
Hydrogen	[t]				0.011
Oxygen	[t]			1.05	
CaO	[t]		0.01		0.001
Na(OH)	[t]			0.08	
Preparation electricity[e]	[GJ_e]	0.8	0.8	0.8	0.8
Electricity	[GJ_e]		0.4	0.1	1.0
Natural gas	[GJ]		3.9	3.3	4.6
Steam	[GJ]				0.1
Outputs:					
Naphtha	[t]		0.47		0.82
BTX	[t]		0.23		
Hydrogen	[t]			0.24	
Heavy oil	[GJ]	38.2[f]			
Process CO_2 emissions	[t]			2.77	
E-gas / pyrolysis gas	[GJ]		7.3		4.0
Hydrogenation residue	[GJ]				0.9
Petcokes	[GJ]		1.1		
Electricity	[GJ_e]			0.2	

[a]Dummy process to model substitution of heavy oil by mixed plastic waste ;[b]Input-output data: (Patel *et al.*, 1998); [c]Input-output data: (Gielen *et al.*, 1994) / own calculations; [d]Input-output data: (Sas *et al.*, 1994), values only refer to part allocated to plastic waste processing (excluding processing of vacuum residue); [e](Patel *et al.*, 1998); [f]To be used as reduction agent in blast furnaces.

Processes for processing unmixed plastic waste

Strictly speaking both mechanical recycling and chemical recycling belong to this category. With mechanical recycling polymers are recovered using mechanical processes like grinding and extrusion. Chemical recycling uses chemicals to recover the building blocks of polycondensation polymers (PUR, PET, PA). In Western Europe a range of processes is used to recover building blocks of polycondensation polymers from specific waste streams, using different chemicals and leading to different outputs. Therefore it is not easy to get an overview on chemical recycling. This, combined with the limited share of chemical recycling in total Western European plastics recycling in 1994 (Patel *et al.*, 1998) made us decide to

confine the analysis to mechanical recycling and not to investigate chemical recycling for this study.

Mechanical recycling

Mechanical recycling of plastic waste is characterised as material reuse while keeping the polymers intact, using only mechanical processes. Regranulate quality is the main concern in mechanical recycling. The more inhomogeneous the material is, the more severe is the material quality loss. Therefore, mechanical recycling of plastic waste to obtain (relatively) 'high quality' regranulate is only possible if the waste stream consists of one defined plastic type. This is the case with industrial plastic waste from plastic processing. Also separately collected products like deprecated used refillable packaging and building materials (window frames, PVC tubes *etc.*) are pure enough to obtain regranulate of acceptable quality. However, only a limited part of plastic products can be produced from regranulate, even though it is produced from unmixed plastic waste. Regranulate from mechanical recycling of *mixed* plastic waste has very low quality and can only be used to produce thick products like roadside posts and heavy garden furniture, in which plastic waste mainly substitutes wood.

Mechanical recycling of plastics consists of a number of steps, including cleaning, removal of unwanted materials, grinding, drying, melting, extruding and granulation (Sas *et al.*, 1994). According to Sas *et al.* approximately 90% of the input plastic waste can be processed into regranulate, the other 10% ends up as waste.

Sas *et al.* give the following energy requirements (virtually only electricity):

- LDPE film: 2.9 – 4.0 GJ_e per tonne plastic waste input
- HDPE bottles: 2.7 – 3.1 GJ_e per tonne plastic waste input
- PET bottles: 1.1 – 1.5 GJ_e per tonne plastic waste input

According to Patel *et al.* (1998) energy requirement for mechanical recycling of PET bottles amounts to 5 GJ_e per tonne plastic waste input. They also give values for the energy requirement of recycling of PVC window frames, floor covering and roofing: 1.3, 3.2 and 2.9 GJ_e per tonne plastic waste input respectively. Based on this relatively wide range of values we estimate the mean electricity requirement for mechanical recycling at 2.5 GJ_e per tonne plastic waste input.

4.3.6 Feedstocks and auxiliary materials

This paragraph concerns all other processes that play a role in the plastics lifecycle. Their products have a wide range of applications, only a limited part of Western European production capacity is actually used to produce the feedstocks and auxiliary materials that are

used in plastics production. Because these processes are not typical 'plastics producing processes' we do not discuss them in detail, but present the data and its sources.

Crudes extraction and feedstock production

Steamcracker feedstocks are produced from crude oil (naphtha, gas oil, LPG) or from natural gas (ethane). Both are extracted from the earth using processes that require energy and that emit CO_2. This is also the case when crude oil is distilled in a number of fractions, including naphtha, gas oil and LPG. Table 20 shows input-output data for the processes involved in the production of steamcracker feedstocks.

Table 20 Material and energy inputs and outputs of processes for crudes extraction and feedstocks production

	unit	Crude oil extraction [a,b]	Crude oil distillation [a]	Natural gas extraction [c]
Inputs:				
Crude oil from oil fields	[t]	1.00		
Crude oil	[t]		1.00	
Natural gas in gas fields	[t]			1.03
Fuel oil	[GJ]	0.99	1.85	
Natural gas	[GJ]			0.13
Electricity	[GJ_e]		0.03	1.08
Steam	[GJ]		0.07	
Outputs:				
Crude oil	[t]	**1.00**		
CDU products [d]	[t]		**1.00**	
Natural gas	[t]			**1.00**

[a]Source: (Van Heijningen *et al.*, 1992a); [b]Including energy use for transportation from oil fields to Western Europe; [c]Source: (GEMIS, 1998), based on German mix of natural gas use (Natural gas from Germany: 18%, The Netherlands: 17%, Norway 33%, Russia 34%). Including energy use for transportation from gas fields to CDU (Germany). [d]Products of Crude Distillation Unit: naphtha, gas oil, LPG (and other products that are of no interest for the plastics lifecycle)

Auxiliary materials production

Besides materials that are derived from steamcracker products a number of other materials is used in the plastics lifecycle. In our study they are indicated as auxiliary materials. Table 21 gives an overview of the most important auxiliary materials used in the plastics lifecycle, with calculated values for the amount of materials needed.

Table 21 Amounts of auxiliary materials needed for the total Western European plastics production in 1994

Auxiliary material	**Production processes**	**Use**[a] [ktonne]
Chlorine	VCM, PUR	3965
Oxygen	VCM, PET, PUR, Plastic waste gasification	2509
Nitric acid	PUR	938
Ammonia	ABS, nitric acid	572
Carbon Monoxide	PUR	449
Formaldehyde	PUR	417
Methanol	PET, formaldehyde	259
Hydrogen	*p*-xylene, PUR, plastic waste hydrogenation	110

[a]Based on model calculations (mind that PUR is chosen as representative for the whole group of thermosets and ABS for 'other thermoplastics'; Therefore, these values may differ from actual uses.

Table 22 shows input-output data for the production of the auxiliary materials that are needed for plastics production.

Table 22 Material and energy inputs and outputs of processes for auxiliary materials production

	Unit	Oxygen [a]	Chlorine [b]	Ammonia	CO [e]	Hydrogen [f]	Methanol [g]	Nitric Acid [h]	Formal-dehyde [k]
Inputs:									
Rock salt	[t]		0.85						
Natural gas feedstock	[t]			0.46[c]	0.55	1.99	0.56		
Ammonia	[t]							0.28	
Methanol	[t]								0.43
Air	[t]	5.0						[m]	[m]
Water	[t]		[n]	[n]	[n]	[n]	[n]		
Fuel oil	[GJ]								
Natural gas	[GJ]			11.60[c]	22.71	47.25			
Electricity	[GJ_e]	1.01	5.90		1.02	2.00	0.32	0.11	0.29
Steam	[GJ]		2.70						
Outputs:									
Oxygen	[t]	**1.00**							
Chlorine	[t]		**1.00**						
Ammonia	[t]			**1.00**					
Carbon monoxide	[t]				**1.00**				
Hydrogen	[t]					**1.00**			
Methanol	[t]						**1.00**		
Nitric Acid	[t]							**1.00**	
Formaldehyde	[t]								**1.00**
Process CO_2 emissions	[t]			1.24[d]		4.6	0.16		
Steam	[GJ]				0.75			2.40	0.60
Hydrogen	[GJ]		1.58						

[a](Van Heijningen *et al.*, 1992b). Electricity use refers to oxygen production only (excluding coupled nitrogen production); [b](Van Heijningen *et al.*, 1992a). Including rock salt extraction. Energy use and hydrogen production refer to chlorine production (excluding coupled sodium hydroxide production); [c](Van Heijningen *et al.*, 1992b); [d](GEMIS, 1998); [e](Chauvel, 1989a): Synthesis gas production via steam reforming of natural gas plus CO absorption. All data refer to CO production only (excluding coupled hydrogen production); [f](GEMIS, 1998): steam reforming of natural gas; [g](Katofsky, 1993): Methanol production from natural gas using CO_2 addition. Steam, heat and part of electricity requirement are provided by heat produced by the process itself; [h](Van Heijningen *et al.*, 1992b); [k](Chauvel, 1989a); [m]Process requires unspecified amount of air; [n]Process requires unspecified amount of water.

4.4 Results

In this section we present the results of the calculations on the energy consumption and total CO_2 emissions by the Western European lifecycle of plastics. The results are summarised in Table 23 and Table 24. Table 23 shows the total energy consumption per process of the

plastics lifecycle in 1994. The first column shows the amount of products and materials that was produced to fulfil the needs of the Western European lifecycle of plastics. The second and third columns respectively show net electricity and steam consumption (calculated as gross output minus gross input). The fourth column shows gross fuels consumption (fuel oil plus natural gas consumption plus internal combustion of fuels that are produced as by-products). In the fifth and sixth columns the first and first-and-second order primary energy consumption are given, as calculated from net electricity and steam use and gross fuels consumption, using the first and first-and-second order energy intensities from the appendix. The production of fuels as by-products of the processes in the plastics lifecycle is shown in the last column. These fuels, which are derived from feedstocks, can be used to fulfil (part of) the fuels requirement in the plastics lifecycle, reducing the amount of fuel oil and natural gas needed. Net fuels consumption for the whole plastics lifecycle is calculated in the last rows of Table 23.

Table 23 Total energy use of processes in the Western European plastics lifecycle in 1994

	Production [ktonne]	**Net electricity use** [PJ_e]	**Net steam use** [PJ]	**Gross fuels use**[b] [PJ]	**1st order primary energy use** [PJ]	**1st and 2nd order primary energy** [PJ]	**Fuels production** [PJ]
Crudes extraction and feedstock production:							
Crude oil extraction	36061[a]			35.7	35.7	38.1	
Natural gas extraction	2016[a]	2.2		0.3	5.5	6.2	
Crude oil distillation	36061[a]	1.1	2.5	66.7	72.1	77.1	
Total		**3.3**	**2.5**	**102.7**	**113.3**	**121.3**	
Alkenes production:							
Ethane steamcracking	1001[a,c]	0.1		14.1	14.3	15.3	12.3
LPG steamcracking	2246[a,c]	0.4		24.4	25.3	27.0	47.2
Naphtha steamcracking	19540[a,c]	2.1	-6.7	170.8	168.5	180.2	257.3
Gas oil steamcracking	5827[a,c]	0.7	-3.2	54.5	52.6	56.3	125.1
Total	**28614** [a,c]	**3.3**	**-9.8**	**263.8**	**260.8**	**278.9**	**442.0**
Intermediates production:							
Butadiene	2231[a]	1.5	17.0		22.6	24.3	
Benzene	4226[a]	0.3	7.7	4.4	13.7	14.7	
Toluene	265[a]	0.0	1.0		1.1	1.2	
p-Xylene	1130[a]	1.1	7.3	6.7	17.5	18.9	4.5
Styrene	4284[a]	1.4	1.3	20.9	25.7	27.6	
VCM	4936[a]	1.5	26.4	21.1	54.1	57.9	
Total		**5.9**	**60.7**	**53.1**	**134.6**	**144.6**	**4.5**

	Production [ktonne]	Net electricity use [PJ_e]	Net steam use [PJ]	Gross fuels use[b] [PJ]	1st order primary energy use [PJ]	1st and 2nd order primary energy [PJ]	Fuels production [PJ]
Polymers production:							
LDPE liquid phase	3914[e]	12.1	-1.6		27.2	31.0	
LLDPE gas phase	783[e]	1.6	0.2		4.0	4.5	
LLDPE solution / suspension	522[e]	0.9	0.8		3.0	3.4	
HDPE gas phase	333[e]	0.7	0.1		1.7	1.9	
HDPE solution / suspension	2998[e]	5.1			12.2	13.8	
PP liquid phase	1488[e]	3.1	1.8		9.4	10.6	
PP gas phase	1488[e]	3.1	1.2		8.8	9.9	
PP suspension	1488[e]	3.1	2.7		10.4	11.6	
PS	2107[e]	1.4	3.3	0.5	7.3	8.1	
PVC	4839[e]	4.8	13.5	3.5	29.8	32.5	
PET	1766[e]	4.4	7.3	12.2	30.8	33.6	
Other thermoplastics (ABS)	2807	5.1	3.5	2.6	18.6	20.7	4.6
Thermosets (PUR)	5127	43.9	58.0	-8.7	160.5	178.5	
Total	**29660**	**89.2**	**90.5**	**10.0**	**323.9**	**360.1**	**4.6**
Plastic processing:							
Film extrusion	6694	12.7			30.2	34.3	
Extrusion coating	638	1.2			2.9	3.3	
Sheets extrusion	283	0.5			1.2	1.4	
Thermoforming	1219	15.4			36.7	41.6	
Blow moulding	2456	5.3			12.7	14.4	
Injection moulding	4698	24.5			58.5	66.5	
Foaming	1980	0.7		1.9	3.6	4.0	
Tubes extrusion	2289	3.3			7.9	8.9	
Profiles extrusion	1090	1.6			3.7	4.3	
Cables extrusion	747	1.3			3.2	3.6	
Other plastic processing processes	4162	15.2		0.6	36.8	41.8	
Total	**26256**	**81.7**		**2.5**	**197.4**	**224.0**	
Auxiliary materials production:							
Chlorine	3965	23.4	10.7		67.7	76.1	
Oxygen	2509	2.5			6.0	6.9	
Nitric Acid	938	0.1	-2.3		-2.3	-2.4	
Ammonia	572			6.6	6.6	7.1	
Carbon Monoxide	449	0.5	-0.3	10.2	10.9	11.7	
Formaldehyde (aqueous 37wt%)	417	0.1	-0.2		0.0	0.0	
Methanol	259	0.1			0.2	0.2	
Hydrogen	110	0.2		5.2	5.7	6.2	
Total		**26.9**	**7.9**	**22.1**	**95.0**	**105.8**	

	Production [ktonne]	**Net electricity use** [PJ_e]	**Net steam use** [PJ]	**Gross fuels use**[b] [PJ]	**1st order primary energy use** [PJ]	**1st and 2nd order primary energy** [PJ]	**Fuels production** [PJ]
Plastic waste management:							
Disposal	13488			1.9	1.9	2.0	
Incineration without heat recovery	561						
Incineration with heat recovery	2348	-17.9			-42.8	-48.6	
Blast furnace injection	5	0.0			0.0	0.0	
Pyrolysis	0						
Gasification / hydrogen production	26	0.0		0.1	0.1	0.1	
Hydrogenation	20	0.0	0.0	0.1	0.2	0.2	0.1
Mechanical recycling	2803	7.0			16.7	19.0	
Total	**19251**	**-10.9**	**0.0**	**2.1**	**-23.9**	**-27.3**	**0.1**
Grand total		**199.4**	**152.1**	**456.1**	**1101.0**	**1207.6**	**451.1**
Avoided[d]				**451.1**	**451.1**	**481.1**	
Net use		**199.4**	**152.1**	**5.0**	**649.9**	**726.1**	

[a]Calculated values for the production of feedstocks for plastics (excluding the production of feedstocks for other products and fuels); [b]Including internal combustion; [c]Sum of ethylene, propylene, C4 and BTX production; [d]Production of fuels as by-products; [e]Excluding 10% regranulate from mechanical recycling (total consumption of PE, PP, PS, PVC and PET = 24249 ktonne, total production of regranulate = 0.9*2803 = 2523 ktonne ~ 10% of total consumption)

Table 24 presents the CO_2 emissions connected to the plastics lifecycle. The first column shows the process CO_2 emissions including the emissions from internal combustion of fuels produced as by-products. In the second and fifth columns gross CO_2 emissions from fuels combustion are given, as calculated from gross energy consumption and the first and first-and-second order CO_2 emission factors from the appendix. The third and sixth columns show the CO_2 emissions that were avoided because of the production of steam and electricity, whereas the fourth and seventh columns show net CO_2 emissions, calculated as process CO_2 emissions plus energy CO_2 emissions minus avoided CO_2 emissions.

Table 24 Total first and first-and-second order CO_2 emissions from processes in the Western European plastics lifecycle in 1994

		1st Order			1st and 2nd Order		
	Process CO_2 emissions [a]	**Energy CO_2 emissions**	**Avoided CO_2 emissions**	**Net CO_2 emissions [b]**	**Energy CO_2 emissions**	**Avoided CO_2 emissions**	**Net CO_2 emissions [b]**
	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]
Crudes extraction and feedstock production:							
Crude oil extraction		2.6		2.6	3.1		3.1
Natural gas extraction		0.2		0.2	0.3		0.3
Crude oil distillation		5.2		5.2	6.2		6.2
Total		**8.0**		**8.0**	**9.7**		**9.7**
Alkenes production:							
Ethylene from ethane steamcracking	0.2	0.1[c]		0.4	0.2		0.4
Ethylene from LPG steamcracking	1.2	0.0[c]		1.4	0.0		1.4
Ethylene from naphtha steamcracking	8.5	0.2[c]	0.5	9.1	0.3	0.5	9.1
Ethylene from gas oil steamcracking	2.3	0.1[c]	0.2	2.5	0.1	0.3	2.5
Total	**12.2**	**0.5**[c]	**0.7**	**13.3**	**0.6**	**0.8**	**13.4**
Intermediates production:							
Butadiene		1.4		1.4	1.6		1.6
Benzene		0.9		0.9	1.1		1.1
Toluene		0.1		0.1	0.1		0.1
p-Xylene		1.1		1.1	1.3		1.3
Styrene		3.3	1.5	1.8	3.8	1.7	2.1
VCM		3.6		3.6	4.2		4.2
Total		**10.5**	**1.5**	**9.0**	**12.1**	**1.7**	**10.4**
Polymers production:							
LDPE liquid phase		1.2	0.1	1.1	1.6	0.1	1.5
LLDPE gas phase		0.2		0.2	0.2		0.2
LLDPE solution / suspension		0.2		0.2	0.2		0.2
HDPE gas phase		0.1		0.1	0.1		0.1
HDPE solution / suspension		0.5		0.5	0.7		0.7
PP liquid phase		0.5		0.5	0.6		0.6
PP gas phase		0.4		0.4	0.5		0.5
PP suspension		0.5		0.5	0.6		0.6
PS		0.4		0.4	0.5		0.5
PVC		1.7		1.7	2.0		2.0
PET	0.4	1.8		2.2	2.1		2.5
Other thermoplastics (ABS)		1.0		1.0	1.2		1.2
Thermosets (PUR)	1.0	8.2		9.2	9.8		10.8
Total	**1.4**	**16.6**	**0.1**	**17.9**	**20.2**	**0.1**	**21.4**

	Process CO_2 emissions [a]	1st Order			1st and 2nd Order		
		Energy CO_2 emissions	Avoided CO_2 emissions	Net CO_2 emissions [b]	Energy CO_2 emissions	Avoided CO_2 emissions	Net CO_2 emissions [b]
	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]	[Mtonne]
Plastic processing:							
Film extrusion		1.3		1.3	1.7		1.7
Extrusion coating		0.1		0.1	0.2		0.2
Sheets extrusion		0.1		0.1	0.1		0.1
Thermoforming		1.6		1.6	2.1		2.1
Blow moulding		0.5		0.5	0.7		0.7
Injection moulding		2.5		2.5	3.3		3.3
Foaming		0.2		0.2	0.2		0.2
Tubes extrusion		0.3		0.3	0.4		0.4
Profiles extrusion		0.2		0.2	0.2		0.2
Cables extrusion		0.1		0.1	0.2		0.2
Other plastic processing processes		1.6		1.6	2.1		2.1
Total		**8.5**		**8.5**	**11.1**		**11.1**
Auxiliary materials:							
Oxygen		0.3		0.3	0.3		0.3
Chlorine		3.2		3.2	4.0		4.0
Nitric Acid		0.0	0.2	-0.2	0.0	0.2	-0.2
Ammonia	0.7	0.4		1.1	0.4		1.1
Carbon Monoxide		0.6	0.0	0.6	0.6	0.0	0.6
Formaldehyde (aqueous 37wt%)		0.0	0.0	0.0	0.0	0.0	0.0
Methanol	0.0	0.0		0.0	0.0		0.1
Hydrogen	0.5	0.3		0.8	0.3		0.8
Total	**1.3**	**4.8**	**0.2**	**5.8**	**5.7**	**0.2**	**6.8**
Plastic waste management:							
Disposal		0.1		0.1	0.2		0.2
Incineration without heat recovery	1.6			1.6			1.6
Incineration with heat recovery	6.8		1.8	4.9		2.4	4.3
Blast furnace injection		0.0		0.0	0.0		0.0
Pyrolysis							
Gasification / hydrogen production	0.1	0.0	0.0	0.1	0.0	0.0	0.1
Hydrogenation		0.0		0.0	0.0		0.0
Mechanical recycling		0.7		0.7	0.9		0.9
Total	**8.4**	**0.9**	**1.8**	**7.5**	**1.1**	**2.4**	**7.2**
Grand total	**24.7**	**49.8**	**4.4**	**70.1**	**60.5**	**5.3**	**79.9**

[a]Including CO_2 emissions from internal combustion of produced fuels; [b]Calculated as process CO_2 emissions plus energy CO_2 emissions minus avoided CO_2 emissions; [c]Excluding CO_2 emissions from internal combustion of produced fuels

4.5 Discussion

In this section the results of the calculations are discussed. Paragraph 4.5.1 treats the total energy consumption of the Western European lifecycle of plastics, whereas paragraph 4.5.2 deals with its total CO_2 emissions. Consequently, in paragraph 4.5.3, differences in energy consumption and CO_2 emissions between plastic types are discussed. Paragraph 4.5.4, finally, discusses the accuracy of the results of the calculations.

4.5.1 Total energy consumption of the Western European plastics lifecycle

Table 23 shows that 36061 ktonne of crude oil and 2016 ktonne of natural gas were consumed in 1994 as feedstocks for the Western European lifecycle of plastics. Together these feedstocks have an energetic value (based on LHV) of 1560 PJ. As can be read from Table 23, 451 PJ of these feedstocks (29%) were processed into fuels as by-products of the processes of the plastics lifecycle. So *net* feedstock consumption amounted to 1109 PJ. The gross energy use (first and second order) of the Western European plastics lifecycle in 1994 amounted to 1208 PJ (Table 23). Thus in total 2317 PJ of primary energy carriers (feedstocks plus fuels) were used in the Western European plastics lifecycle. Total Western European use of primary energy carriers amounted to about 52500 PJ in 1994 (IEA, 1997). So it follows that the plastics lifecycle used 4.4% of total Western European use of primary energy carriers in 1994, 2.1% of which were used as feedstock and 2.3% as fuel.

Figure 6 shows the first and second order primary energy consumption (used as fuels) of the plastics lifecycle, divided by stages of life[12]. Figure 6 shows that all stages make non negligible contributions to the total energy consumption. However, it can be seen that the stages alkenes production, polymers production and plastics processing have relatively high shares of total energy consumption. All stages except plastic processing are part of the chemical industry. This means that the chemical industry consumes 82% of total energy consumption, whereas the plastics processing industry consumes 18% over the life-cycle.

Thus, although the largest part of energy requirement (and of the CO_2 emissions) in the plastics lifecycle take place in the chemical industry, the contribution of the plastics processing industry is also considerable. Several authors (for example (Novem, 1997), (Mulder, 1994), (Van der Leest, 1996) and (Tonino, 1996)) have stated that a large potential for energy efficiency improvement (30-50%) exists in this industry. The plastics processing industry is composed of a large number of small companies, in which the reduction of energy consumption has yet gained little attention.

[12] In Figure 6, plastic waste management is not shown. Plastic waste management delivers 2.2% of the energy used in the plastics lifecycle.

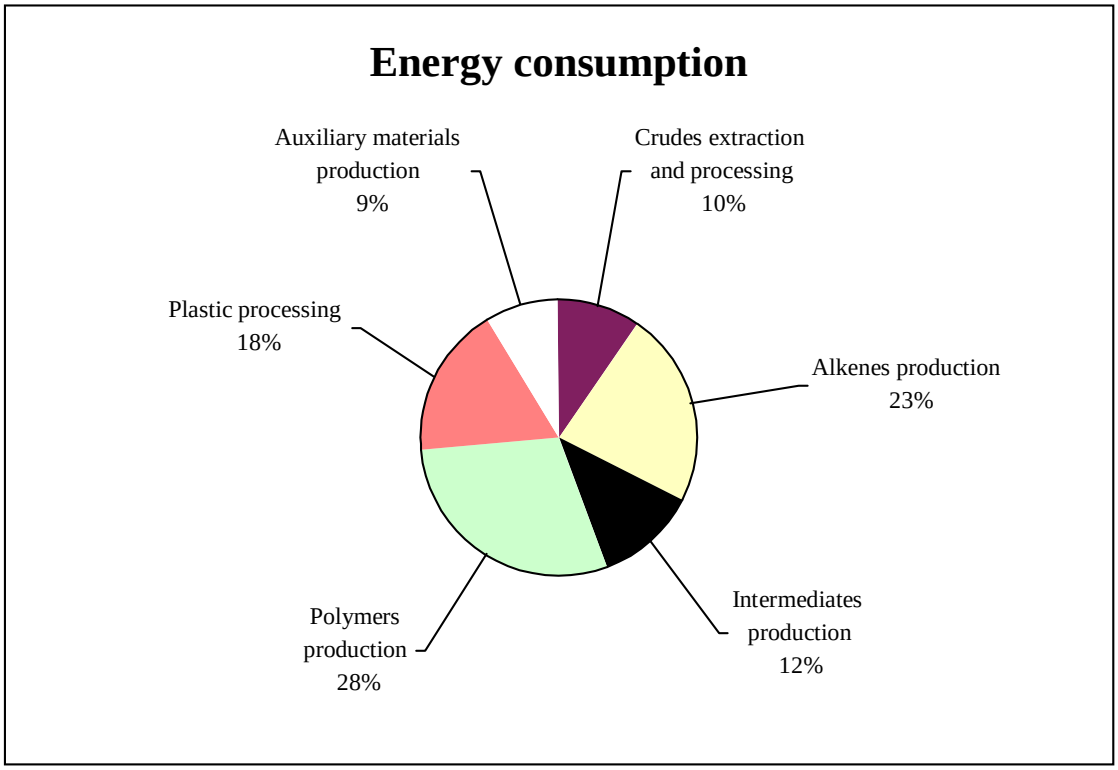

Figure 6 First and second order energy consumption in the Western European plastics lifecycle in 1994, by stages of life

4.5.2 Total CO_2 emissions of the Western European plastics lifecycle

The results of the calculations show that 79.9 Mtonne of CO_2 were emitted in the Western European plastics lifecycle in 1994 (Table 24). Total Western European CO_2 emissions in 1994 are estimated at 3500 Mtonne (Gielen, 1997). This means that 2.3% of Western European CO_2 emissions were directly or indirectly related to the production and processing of plastics. This share is considerably smaller than the share of the consumption of primary energy carriers by the plastics lifecycle in the total Western European consumption of primary energy carriers (4.4%).

In 1994 only a small part of the carbon content of feedstocks used for plastics production was released as CO_2. This is partly due to the fact that the amount of plastics that were produced in 1994 (29660 ktonne) largely exceeds the amount of plastics that left the plastics lifecycle (16448 ktonne[13]). This effect is further enhanced by the fact that plastic waste combustion and gasification (the processes that convert the carbon content of plastic waste into CO_2 emissions) made up only 27% of final plastic waste management in 1994. Therefore, CO_2

[13] 19251 ktonne - 2803 ktonne (mechanical recycling) = 16448 ktonne

emissions from plastic waste combustion and gasification were relatively small (8.4 Mtonne: 0.3% of total Western European CO_2 emissions).

A division of CO_2 emissions between stages of life is shown in Figure 7. From this division it can be seen that polymers production makes the largest contribution, followed by alkenes production and plastic processing. From Figure 7 it can be derived that 77% of the CO_2 emissions in the Western European plastics lifecycle were associated to processes in the chemical industry, 14% to processes in the plastics processing industry and 9% to plastic waste processing.

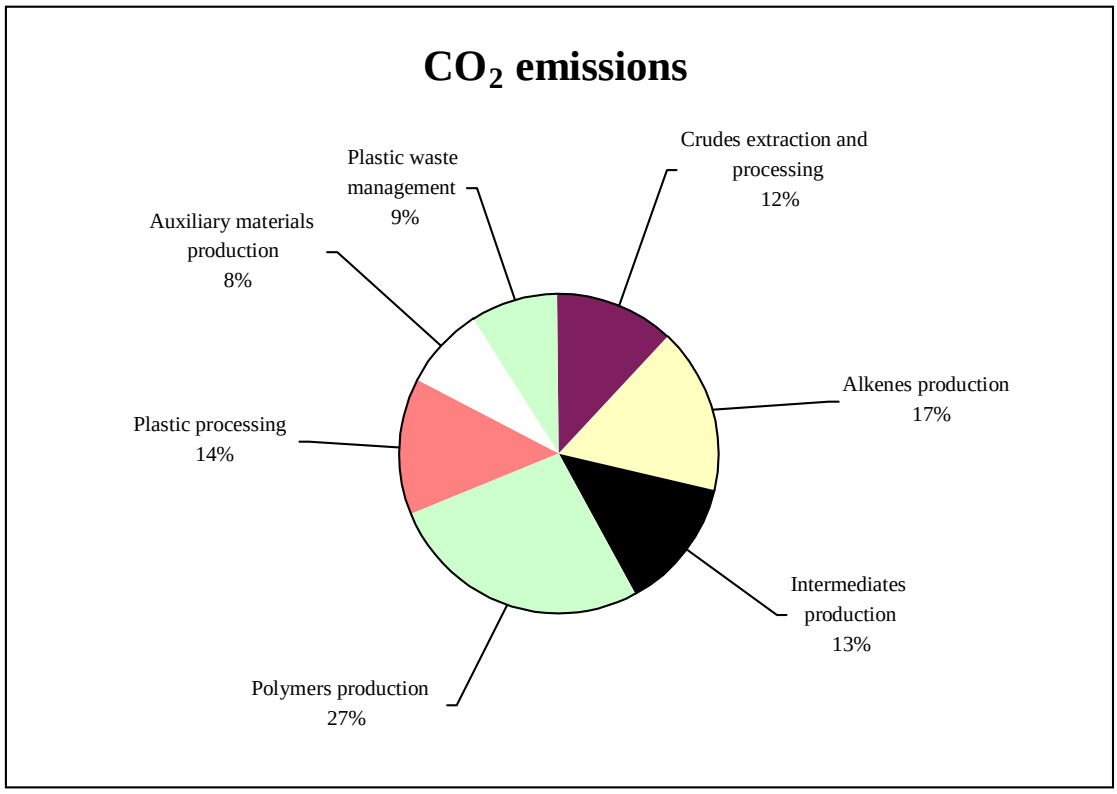

Figure 7 First and second order CO_2 emissions from the Western European plastics lifecycle in 1994, by stage of life

Comparison of Figure 6 and Figure 7 shows that the divisions of energy consumption and CO_2 emissions by stages of life are quite similar. This is because 84% of the total CO_2 emissions[14] from the plastics lifecycle are caused by fuels combustion.

[14] According to Table 24, total CO_2 emissions (first and second order) amount to 79.9 Mtonnes. 55.2 Mtonnes of these are related to the consumption of the energy carriers natural gas, fuel oil, electricity and steam. 12.2 of the 24.7 Mtonnes of process CO_2 emissions stem from internal combustion of fuels that are produced as by-products and are, therefore, also related to energy consumption. So in total 67.4 Mtonnes (84%) of CO_2 emissions are related to energy consumption.

4.5.3 Differences between plastic types

Table 11, Table 12 and Table 13 show that energy requirements to produce 1 tonne of plastics differ considerably between plastic types. The total final energy requirements to produce PET and thermoplastics prove to be considerably higher than the energy required to produce PE, PP, PS or PVC. This effect is partly caused by our way of modelling (intermediates production for PS and PVC are excluded from the calculated values for PS and PVC production, whereas intermediates production for PET and PUR are included in the results for PET and thermoplastics production). Nevertheless, the large number of sub-processes needed to produce PET and PUR increases the total energy requirement and CO_2 emissions compared to the energy requirements and CO_2 emissions connected to the production of PE, PP, PS or PVC. Especially the final energy requirement for PUR production of 18.2 GJ/tonne is considerably higher than the final energy requirements to produce the other plastics discerned in our study.

Taking the production of PUR as a representative for the production of all thermosets, we calculated that a large share (50%) of the energy requirement for polymers production in Western Europe is due to the production of thermosets. This is in sharp contrast to the limited share (17%) of thermosets production in total plastics production. In practice energy consumption for the production of thermosets may even be higher. Literature data indicate that energy requirements for the production of a number of thermosets even exceeds the energy consumption[15] for PUR production: for example epoxy: 29.6 GJ/tonne and polyamide: 44.0 GJ/tonne (Patel *et al.*, 1998).

4.5.4 Accuracy of the results

In this study we made some assumptions that may influence the accuracy of the results. From the one hand we made assumptions in the calculation method, from the other hand we made assumptions about the interpretation of the input data from the literature.

Methodological aspects

The aim of this study was to investigate the energy use and CO_2 emissions of the whole Western European plastics lifecycle. Because of the wide scope of this study, we made some choices in order to limit the amount of production processes to be modelled.

Firstly, we did not investigate the energy use and CO_2 emissions of the production of additives that are used in the production of plastics. Especially for PVC, for which an additive content of 10% or more is not uncommon, this may cause inaccuracies. From the other hand,

[15] Excluding feedstocks

by considering the plastics produced to consist entirely of monomer, the omission of the additives is, at least partly, replaced by an increased production of monomers.

A second source of inaccuracies is formed by our way of modelling 'other thermoplastics' and 'thermosets', for which ABS and PUR were chosen as representatives. However, by choosing plastic types of which the consumption makes up a large share of group to which they belong, we have attempted to keep the inaccuracies as small as possible. In Table 25 Gross Energy Requirement[16] values are given for a number of 'other thermoplastics' and thermosets (Patel, 1999). It can be seen that the gross energy requirement of PUR production lies close to the average GER for thermosets. The gross energy requirement of ABS production lies less close to the average GER for 'other thermoplastics', but, given the fact that 'other thermoplastics' make up only 9% of plastics consumption (APME, 1996), the influence on the overall results will be limited.

Table 25 Gross Energy Requirements (GER) for the production of a number of 'other thermoplastics' and thermosets (Patel, 1999)

	Gross Energy Requirement (GER) [GJ/tonne]
Thermosets	
Epoxide resin	107.1
Urea resin	50.3
Melamine resin	79.9
Phenol formaldehyde resins	60.0
Unsaturated polyester / alkyd resins	64.5
Polyurethane (PUR)	**75.5**
Thermosets, average	***72.9***
'Other thermoplastics'	
Nylon-6	122.7
Nylon-6,6	163.0
Polyacrylonitrile	69.3
Polyacrylate	82.6
Polycarbonate	80.3
Polyvinyl acetate	58.2
ABS	**81.7**[a]
'Other thermoplastics', average	***94.0***

[a](Heijningen *et al.*, 1992b)

Furthermore, we did not investigate energy use and CO_2 emissions connected with transport of feedstocks, intermediates, plastics, plastic products and plastic waste.

[16] The Gross Energy Requirement (GER) value of a material is the amount of primary energy that is needed to produce 1 tonne of that material, including the energy needed for the production of feedstocks and energy carriers

Literature data

As the calculations of this study are based on a large amount of input data, a large part of our research effort went into data collection from literature. In gathering these data we faced some difficulties.

Firstly, it was necessary to investigate a large number of chemical processes. Many of these processes consist of a complex pattern of material and energy flows. Furthermore, each process has a number of variants, several of which are used simultaneously in Western Europe. Each variant differs in product yield, energy use and CO_2 emissions. Within the scope of this study it was impossible to investigate all process variants in detail.

The second difficulty was the scarcity of reliable data in literature. It is, for example, very difficult to find reliable data on the distribution of process variants used to produce a specific chemical product in Western Europe. Furthermore, it was impossible to find reliable data on energy use and CO_2 emissions for all process variants that are used. Data collection on chemical processes is further complicated by the fact that the processes are continuously improved. Each year plants are transformed and old plants are replaced by new ones using improved technologies. Therefore, both the division of process variants used in Western Europe and the energy use and CO_2 emissions of the individual processes are changing over time.

Data sources in literature (often implicitly) relate to a specific plant, using a specific process variant in a specific year and in a specific country. Therefore, data sources that apparently concern the same process, may in practise differ considerably. It was beyond the scope of this study to trace the cause of apparently conflicting data. For each process we closely examined the data in the literature. When facing conflicting data we considered how to use them. In some cases we used the average, in other cases we rejected one data source in favour of a more recent one, or one that seemed more reliable.

4.6 Conclusions

In this study we have calculated total energy requirement and total CO_2 emissions from processes in de Western European plastics lifecycle in the year 1994. From our calculations it follows that 2317 PJ of energy carriers were used, 4.4% of the total Western European consumption of energy carriers. 1109 PJ (2.1%) were used as feedstocks and 1208 PJ (2.3%) as fuels. Our calculations also show that the Western European plastics lifecycle produced 79.9 Mtonne of CO_2 emissions, a contribution of 2.3% of total Western European CO_2 emissions.

Our study shows that all stages of the lifecycle (crudes extraction and processing, alkenes production, intermediates production, polymers production, plastics processing, auxiliary materials production and plastic waste management) make non negligible contributions to the total energy consumption and CO_2 emissions of the plastics lifecycle. However, energy use and CO_2 emissions from polymers production, alkenes production and plastics processing are the most extensive.

The largest share (28%) of the energy carriers that were consumed in the plastics lifecycle was used for the production of polymers. This stage also produced the largest share (27%) of CO_2 emissions. We calculated that more than half of the energy consumption for polymers production was due to the production of thermosets, which is highly energy intensive. There are two ways to reduce the total energy consumption for the production of thermosets, firstly by improving the various sub-processes in the production of thermosets, secondly by substitution of thermosets by other less energy-intensive materials where possible. Further research should focus on the possibility of these measures.

The second large energy consuming stage in the plastics lifecycle, alkenes production consumed 23% of the total energy consumption of the plastics lifecycle, whereas it accounted for 17% of the CO_2 emissions. Energy consumption in alkenes production has decreased considerably during the past decades. Specifications of modern, up to date steamcrackers show that further energy efficiency improvements may be expected in the nearby future, when old steamcrackers will be supplanted by new ones. Further efficiency improvements in alkenes production may be achieved by using new technologies that are currently under development, like oxidative coupling of natural gas, the methanol to olefins process, or biomass pyrolysis. These technologies, which may largely influence material flows in the plastics lifecycle, may induce reductions of energy consumption and CO_2 emissions in several stages of the lifecycle simultaneously.

Our calculations show that plastics processing is the third large energy consuming stage in the plastics lifecycle: it accounts for 18% of total energy consumption and 14% of total CO_2 emissions. It is expected that large energy saving potentials exist in plastics processing (Novem, 1997). Unlike the chemical industry, the plastics processing industry consists of a large number of relatively small companies. In these companies energy efficiency improvement has not yet gained much attention. This, in combination with the large share of the plastics processing industry in total energy consumption, indicates that considerable energy savings are achievable in this industry. Although the implementation of energy saving measures may be rather difficult, it appears to be profitable to put much effort into the investigation of possible measures for the reduction of energy consumption and CO_2 emission in plastics processing.

The calculation method presented in this study can be extended in order to facilitate a study on the effects of changes in the plastics lifecycle, like shifts to different plastic types, different feedstocks for alkenes production or different plastic waste management options. This will be the object of chapter 5.

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4.8 Appendix: Energy intensities and CO_2 emission factors of energy carriers

4.8.1 Energy intensities

Energy intensities are used to account for the energy required for the production of energy carriers. By multiplying the direct energy consumption of the processes in the plastics lifecycle by these energy intensities, the total primary energy consumption associated with the use of energy carriers is calculated. We distinguish two types of energy intensities: First order energy intensities and first-and-second order energy intensities. First order energy intensities account for the energy requirement of steam and electricity production. The first order energy intensity is equal to 1 divided by the conversion yield. For fuel oil and natural gas no conversion is needed, so their first order energy intensities are equal to 1 [J/J]. Yields of steam and electricity production vary with the primary fuels that are used. We calculated the mean first order energy intensity for steam and electricity production from fuel mixes and conversion yields as shown in Table 26.

Table 26 Calculation of the mean first order energy intensity for electricity and steam

Electricity production

Fuel	**Share in Western European electricity production[a]**	**Conversion yield[b]**	**Contribution to mean 1st order energy intensity**
	[%]	[%]	[J/J]
Fuel oil	9.6	42	0.23
Natural gas	9.5	33	0.29
Coal	18.5	39	0.47
Lignite	10.5	39	0.27
Nuclear	36.2	33	1.10
Hydro	15.6		
Total	**100**	**42**	**2.36**

Steam production

Fuel	**Share in Western European steam production[b]**	**Conversion yield**	**Contribution to mean 1st order energy intensity**
	[%]	[%]	[J/J]
Fuel oil	40	90	0.4
Natural gas	50	90	0.56
Coal	10	90	0.11
Total	**100**	**90**	**1.11**

[a](SimaPro, 1998); [b](GEMIS, 1998)

First-and-second order energy intensities additionally account for the energy consumption of the production of primary fuels (including fuels for steam and electricity production). The first-and-second order energy intensity for fuel oil and natural gas is calculated from data on crude oil extraction and distillation and natural gas extraction, as described in paragraph 4.3.6. The first-and-second order energy intensities for electricity and steam is taken from (Van Heijningen *et al.*, 1992). The values used in our study are presented in Table 3.

4.8.2 CO_2 emission factors

CO_2 emission factors are used to calculate the CO_2 emissions from the production and combustion of the energy carriers that are used in the plastics lifecycle. The first order CO_2 emission factor accounts for the CO_2 emissions from fuels combustion in steam and electricity production.

The first order CO_2 emission factor is calculated from CO_2 emission factors of fuels combustion that are derived from Gielen (1997) and the distribution of fuels used in steam and electricity production from SimaPro (1998) and GEMIS (1998).

The first-and-second order CO_2 emission factor also includes CO_2 emissions from fuels extraction and processing (including fuels for steam and electricity production). CO_2 emission factors for the production and combustion of fuels are derived from (SimaPro, 1998). They are used to calculate the first-and-second order CO_2 emission factors for electricity and steam, as shown in Table 27.

Table 27 Calculation of second order CO_2 emission factors for electricity and steam

Electricity production

Fuel	**Share in Western European electricity production** [a]	**CO_2 emissions from fuels production and combustion** [a]	**Contribution to mean 1st and 2nd order CO_2 emission factor**
	[%]	[kg / GJ_e]	[kg / GJ_e]
Fuel oil	9.6	244	23
Natural gas	9.5	213	20
Coal	18.5	272	50
Lignite	10.5	375	39
Nuclear	36.2	2	1
Hydro	15.6	0	0
Total	**100**		**134**

Steam production

Fuel	**Share in Western European steam production** [b]	**CO_2 emissions from fuels production and combustion** [a]	**Contribution to mean CO_2 emission factor**
	[%]	[kg / GJ]	[kg / GJ]
Fuel oil	40	88	39
Natural gas	50	57	32
Coal	10	96	11
Total	**100**		**82**

[a](SimaPro, 1998); [b](GEMIS, 1998)

The CO_2 emission factors used in this study are summarised in Table 3.

Chapter 5

The impact of structural changes in the Netherlands lifecycle of plastics on the consumption of fossil fuels and the emission of CO_2[1]

Abstract

In this study technological measures are investigated to simultaneously reduce CO_2 emissions and fossil fuels and feedstocks consumption in the lifecycle of plastics. These measures primarily involve structural changes in alkenes production, polymers production and plastic waste management. A method is presented to calculate the influences of these changes on the consumption of fossil feedstocks and fuels, CO_2 emissions and costs of the total lifecycle. It is concluded that especially processes based on biomass feedstocks, mechanical recycling, selective dissolution and blast furnace injection are most promising options for reducing total lifecycle CO_2 emissions and fossil fuels and feedstocks consumption. We estimate that in The Netherlands lifecycle of plastics a total reduction in the consumption of fossil feedstocks and fuels of up to 60% and a CO_2 emission reduction of up to 30% may be achievable by a combination of promising options. Realisation of these options may be accompanied by a cost increase of the total plastics lifecycle of about 20%.

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5.1 Introduction

5.1.1 The consumption of fossil fuels in the lifecycle of plastics

To achieve a more sustainable development of society, an efficient use of natural resources and a proper management of the atmosphere is required (WCED, 1987, UNCED, 1993). More focussed, attention should be given to a more sustainable use of fossil fuels and a reduction of CO_2 emissions (WEA,2000). In this study we focus on the use of fossil fuels and the emissions of CO_2 that are connected to the production and consumption of plastics.

Although the main application of fossil fuels is the deliverance of energy, a substantial part of the fossil fuels (11-12% in Western Europe in 1995 (Patel, 1999)) is used as feedstock for the manufacturing of chemical products, of which plastics are the most important. Apart from the fossil fuels that are needed as feedstocks for plastics, the production processes to produce plastics also require the input of energy. In practise this energy is for the largest part generated from fossil fuels. So the use of plastics implies the consumption of fossil fuels both as feedstock and as energy source. This means that reductions of fossil fuels consumption (and the associated CO_2 emissions) in the lifecycle of plastics can both be achieved by technological measures that aim at a reduction of materials consumption (reduction of feedstocks) and by technological measures that aim at a reduction of energy consumption (reduction of energy sources).

There are several ways to achieve a reduction of *materials consumption* in the lifecycle of plastics, *e.g.*:

- Producing products that are made of less material (downgauging)
- Producing products with longer lifetimes
- Waste prevention and reduction in materials production and processing
- Material recycling

A reduction of *energy consumption* in the lifecycle of materials can be achieved by improvements of the material production processes, or by using materials of which the production is less energy intensive. Furthermore, energy savings are induced by material savings, because less energy is needed for materials production and processing.

During the last decades much effort was put into the investigation and implementation of measures for energy efficiency improvement and / or CO_2 emission reduction. In The Netherlands several industries, including the chemical industry and the plastics processing industry, have signed so-called ‘long-term agreements’ for energy efficiency improvement.

The policy target of the log-term agreements of both the chemical industry and the plastics processing industry was to increase their energy efficiency by 20% in the period 1989-2000. Until 1998 an average energy efficiency improvement of 18.5% was achieved in the chemical industry[2], whereas the energy efficiency in the plastics processing industry was improved by 14.6% (EZ, 2001).

5.1.2 Focus of this study

So far, the largest part of the reductions of fossil fuels consumption and CO_2 emissions was achieved by improvements to specific production processes. The influence of these measures does generally not reach very far beyond the specific processes they are applied to. In this study we focus on technological measures that can have a larger impact on energy use and CO_2 emissions, because they result in structural changes to the lifecycle of materials. These measures, like the use of alternative production routes, substitution between different materials, or enhanced material recycling, potentially lead to high material and energy savings, because savings may be introduced simultaneously in several parts of the lifecycle.

Structural changes come down to shifts between processes. Basically, structural changes to the plastics lifecycle are characterised as an increase of the share of one or more processes, combined with a decrease of the share of one or more other processes.

We focus on the following types of measures:
- Using alternative processes for alkenes production (changing production routes)
- Using alternative plastic types (material substitution)
- Using alternative processes for plastic waste management (increasing materials recycling)

We aim at the development and application of a method to investigate the influences of structural technological measures to improve the efficiency of fossil fuel consumption in the lifecycle of plastics on total material and energy consumption, CO_2 emissions and costs throughout the lifecycle of the materials.

5.1.3 Existing calculation methods

For technological measures that affect large parts of the plastics lifecycle, it may not be easy to estimate the overall effects on materials and energy use, CO_2 emissions and costs. An overview of these effects can only be obtained if a calculation method is used that takes into account all interrelations.

[2] According to the Association of the Dutch Chemical Industry (VNCI) the energy efficiency improvement target of the chemical industry of 20% was amply achieved by the year 2000 (VNCI, 2001)

For this purpose the Netherlands Energy Research Foundation (ECN) has developed a MARKAL (MARKet ALlocation) model, called MATTER (MATerials Technologies for CO_2 Emission Reduction) (Gielen, 1999). This model of the European energy and materials system can be used to investigate the potential development of the use of energy carriers and materials in the period 2000-2050, based on scenarios of the economic development and assumptions about the development of technologies. The model chooses alternative production processes that reduce CO_2 emissions, with lowest costs. The MATTER / MARKAL model is a powerful model to investigate the potential development of the European energy and materials system, taking into account measures to improve the efficiency of energy and material use. However, interpretation of its results is rather difficult. The model includes a large amount of alternative processes for the production of a diverse range of materials, products and energy carriers. Because the final results of the calculations are the combined results of a large number of assumptions and 'decisions' taken by the model, it is often difficult to argue why one specific measure is chosen and another is not.

Olsthoorn *et al.* (2000) describe the so-called FLUX model, a model for the analysis of physical flows and physical stocks in an economy and of associated patterns of environmental pollution. It is a sophisticated, object-oriented model, in which a material balance is constructed, consisting of *nodes*, flows and stocks. For each *node* a relation is defined between inputs, stocks and outputs of materials (including emissions). The model is especially useful for mapping highly complex material flow patterns.

Another, more straightforward method is described by Worrell *et al.* (1995). Their method for analysing the potential for material efficiency improvement in the lifecycle of products consists of the following steps:

1. Analysis of the current consumption of materials embodied in the product of investigation.
2. Analysis of the lifecycle of the product and the materials it contains.
3. Analysis of the energy requirements and costs of the processes that are involved in the different lifecycle stages.
4. Calculation of the total energy requirements and costs.
5. Definition of improvement measures to reduce the amount of materials used.
6. Construction of new lifecycles that are the result of the improvement measures and calculation of the total energy requirement and costs of the new lifecycles.

5.1.4 Our calculation method

As the purpose of our study is to get detailed insight in the effects of specific technological measures in the lifecycle of plastics, application of the MATTER / MARKAL model seems

less suitable. Because of the relatively limited complexity of the lifecycle of plastics, we did not feel the need to apply a sophisticated model for constructing a material balance, like the FLUX model, which should have been extended anyway in order to facilitate the calculation of energy consumption, CO_2 emissions from fuels combustion and costs. Therefore we used a spreadsheet model that follows the method of Worrell *et al.*

We made the following modifications to the method in order to meet our specific purposes.:

- We do not apply the method to a specific product, but to the total consumption of a specific material (plastics) by a specific country (The Netherlands) in a specific year (1990).
- In addition to energy requirements and costs, we also calculate the CO_2 emissions that are involved.
- In the sixth step, we add a calculation of sensitivities, in which the relative changes of total energy consumption, total CO_2 emissions and total costs are calculated, applying a specific measure to a specific part of the materials involved.

The lifecycle of plastics consists of a large number of different products, each demanding specific material properties. Because technological measures for material efficiency improvement influence the material properties, they can, in general, only be applied to part of the plastics. Because of the large amount of different products that are made from plastics, it is virtually impossible to say to which part of the plastics the measures can be applied. This means that the *application potentials* of the measures are essentially unknown. If the application potentials of the measures are unknown, it is also impossible to exactly calculate the material, energy and CO_2 emission reductions that can be achieved by application of those measures. In other words: it is impossible to calculate the *reduction potentials* of those measures (and likewise it is impossible to calculate the total costs that are involved with those measures).

Given these limitations, we aim at providing insight in the *sensitivities* of the total material and energy consumption, CO_2 emissions and costs of the plastics lifecycle for the application of material efficiency improvement measures to a part of the plastics involved.

We use the calculation method to analyse the lifecycle of plastics with respect to its sensitivity for different technological measures aiming at reductions of fossil fuels and feedstocks consumption and CO_2 emissions.

The results of our calculations should not be considered as forecasts, but as alternatives. They give an answer to the question what total fossil feedstock and energy use, CO_2 emissions and costs of the plastics lifecycle might have been if alternative (mixes of) technologies were used. Nevertheless, the results can be interpreted as lessons for the future. They give

indications in which direction the plastics lifecycle could be changed if the object is to decrease materials consumption, energy consumption and CO_2 emissions at minimum costs.

5.2 Methodology

The objective of our calculation method is to investigate the effects of structural changes in the plastics lifecycle in order to improve energy and material efficiencies and to reduce CO_2 emissions in a cost effective way.

Specifically, the method consists of the following steps:

1. Analysis of the consumption of plastics in The Netherlands in 1990.
2. Analysis of the lifecycle of plastics and construction of a material balance[3].
3. Analysis of the energy requirements, CO_2 emissions and costs of the processes that are involved in the lifecycle of plastics.
4. Calculation of the total material and energy requirements, CO_2 emissions and costs in the base case.
5. Definition of improvement measures to reduce the amount of feedstocks, energy carriers and CO_2 emissions.
6. Construction of new material balances that are the result of the improvement measures, calculation of the total material and energy requirements, CO_2 emissions and costs of the new material balances and calculation of sensitivities.

In paragraph 5.2.1 a short description of the plastics lifecycle is given. Paragraph 5.2.2 describes the basis of the analysis and the system boundaries that are used. In paragraph 5.2.3 the composition of the material balance is discussed, whereas the calculation of energy use, CO_2 emissions and costs is described in paragraphs 5.2.4 and 5.2.5. Paragraph 5.2.6 describes the efficiency improvement cases that were studied, whereas paragraph 5.2.7 focuses on the calculation of sensitivities.

5.2.1 The lifecycle of plastics

In this paragraph a short description is given of the lifecycle of plastics. A more extensive description is given in Chapter 3.

The layout of the lifecycle of plastics is shown in Figure 1. It starts with the extraction of crude oil and natural gas. Crude oil is distilled into a number of fractions, of which naphtha, gas oil and LPG are used in steamcrackers to produces alkenes. An alternative for these oil-based feedstocks is the use of natural gas with high ethane content. Other routes for alkenes

[3] The first two steps correspond to a Material Flow Analysis (MFA)

production currently under development are: oxidative coupling of natural gas, the methanol to olefins process and (flash) pyrolysis of biomass. In this study we investigate these routes as alternatives for conventional steamcracking. The main products of alkenes production that are used to produce polymers are ethylene, propylene and a BTX (Benzene, Toluene, Xylene) fraction. The polymers that are obtained are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and a number of other polymers. The production of PS and PVC runs via the intermediates styrene (produced from ethylene and benzene, which is derived from the BTX fraction) and vinyl chloride monomer (produced from ethylene and chlorine).

Polymers are processed into plastic products using a number of processes like extrusion, injection moulding and blow moulding. After a certain period these products are discarded. Discarded plastic products are referred to as post consumer waste. Another stream of plastic waste arises from the production and processing of plastics. Plastic post consumer waste and plastic production and processing waste are treated further using a number of options, including landfilling, incineration and mechanical recycling.

In addition to the conventional options for plastic waste treatment we also discern a number of processes that have more recently become commercially available or which are currently under development: blast furnace injection, selective dissolution, pyrolysis, gasification and hydrogenation. Most plastic waste treatment processes aim at recovering (part of) the material and / or energy contents of the plastics. In principle this results in a decrease of the total consumption of primary materials and / or energy.

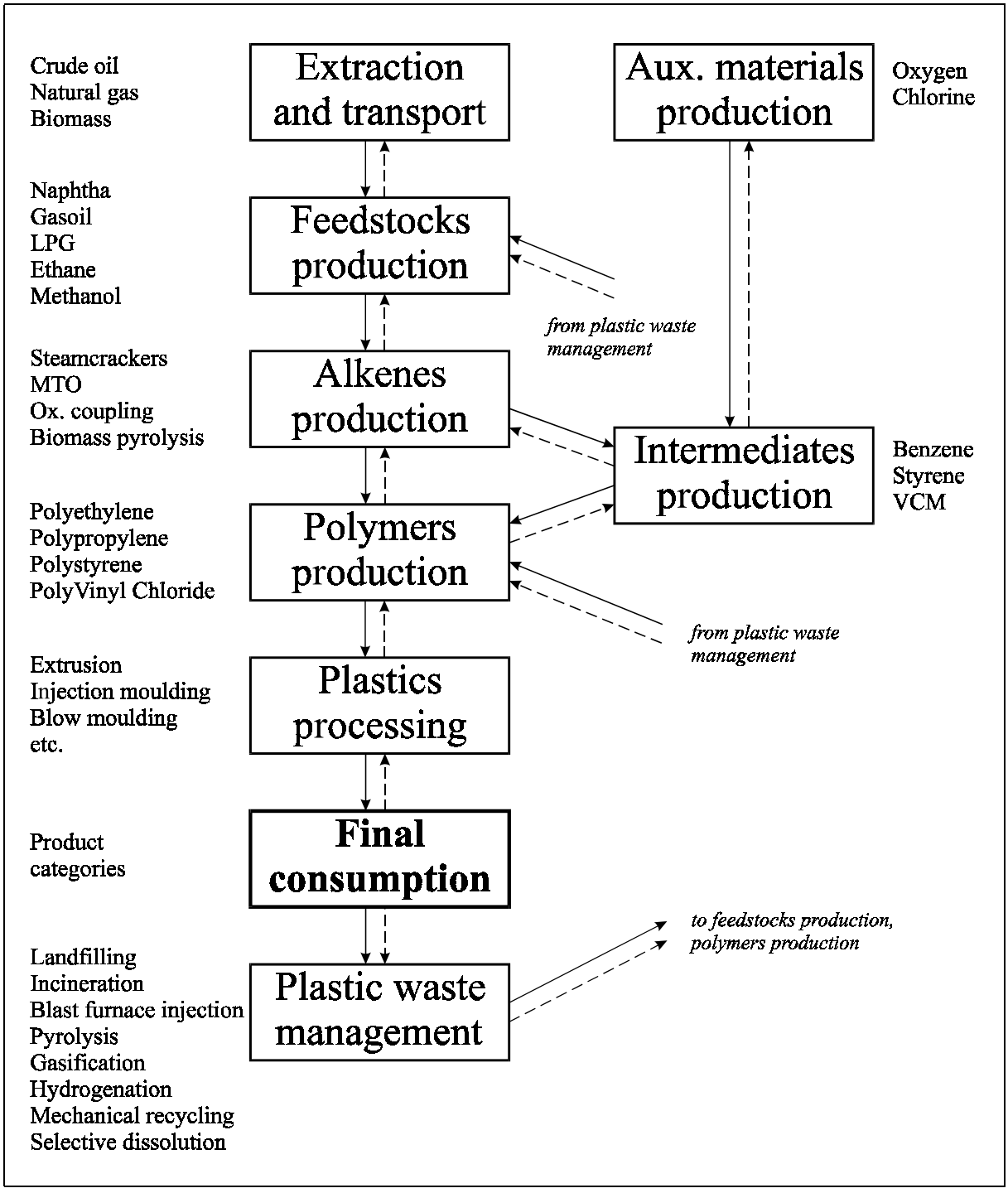

Figure 1 The plastics lifecycle. Continuous arrows indicate material flows. Dotted arrows indicate the sequence of calculation.

5.2.2 Basis of the analysis and system boundaries

Our analysis concerns the plastics lifecycle that is related to the final consumption of plastics in The Netherlands in 1990. The plastics lifecycle encompasses all processes that play a role in the production and processing of plastics and their feedstocks, as well as the processing of plastic waste. In our analysis geographical location plays no role: all processes are taken into account, regardless whether they take place in or outside The Netherlands. Because energy consumption of and CO_2 emissions from transports are relatively small compared to energy consumption of and CO_2 emissions from the processes themselves (Patel *et al.*, 1998), we do not taken them into account. We make an exception for transports of crude oil from the place of extraction to the refineries. Because of the long distances involved, energy use and CO_2 emissions from these transports are not negligible. Furthermore, it should be noted that energy use and CO_2 emissions during the period of final consumption are not accounted as part of the plastics lifecycle.

In Chapter 3 we analysed the final consumption of plastics in The Netherlands in 1990, using the STREAMS method. In this method the final consumption of materials is derived from monetary statistics, the so-called use and supply tables. However, here we do not use the results of this study, but the results of a more refined approach, in which improvements suggested by Hekkert *et al.* (2000) are taken into account[4]. These results are shown in Table 1.

[4] In the original version of the STREAMS method (see Chapter 3 of this thesis) monetary plastic use tables were used, which were converted into physical plastic use tables using mean prices. In the more refined approach of Hekkert *et al.* (2000) physical plastics use tables produced by Statistics Netherlands are used (Konijn *et al.*, 1996). Because Statistics Netherlands uses more accurate prices, more accurate results are obtained. Furthermore, the physical plastic use tables from Statistics Netherlands allow a distinction between various plastic types, whereas in Chapter 3 only one category of primary plastics was discerned.

Table 1 Final consumption of plastics in The Netherlands in 1990 as calculated with the STREAMS method, by product categories of Statistics Netherlands[5]

	Final plastics consumption	
	All plastics	**Bulk plastics only[d]**
Plastic products:		
Plastic building materials	86	67
Plastic industrial components	71	55
Plastic films and sheets, cellular	45	35
Plastic films and sheets, reinforced	22	17
Plastic films and sheets, others	227	177
Plastic tubes	171	134
Plastic rods and profiles	59	46
Plastic floor covering	39	31
Plastic furniture	29	23
Plastic lighting	4	3
Plastic packaging	374	293
Refuse bags	20	16
Adhesive tape	15	11
Plastic office and school supplies	17	13
Other plastic products	157	122
Plastic products, total	**1334**	**1042**
Primary plastics:		
PE/PP	68	
HDPE[a,b]		18
LDPE[a,b]		21
LLDPE[a,b]		7
PP[a]		23
PS	21	21
Polyamide etc.	24	
Polyurethanes	106	
Others, including PVC	52	
PVC[c]		52
Primary plastics, total	**271**	**141**
Total	**1605**	**1183**

[a]Division PE/PP estimated as 2/1, based on the average product yield of naphtha steamcracking; [b]Division HDPE/LDPE/LLDPE calculated from the division of Western European PE production in 1995: 3800/4500/1450 ktonnes respectively (Harzmann *et al.*, 1996), (Kaps *et al*, 1996). [c]Assumption that 'other plastics' mainly consist of PVC; [d]The final consumption of plastic products made of bulk plastics is calculated by taking into account the mean bulk plastic content of the plastic products of 78% that results from the STREAMS calculations.

[5] For the analysis of final plastic consumption in The Netherlands in 1990 using the STREAMS method (Chapter 3) statistical data of Statistics Netherlands were used, in which the use of plastic products is subdivided into the product categories shown.

In reality many different plastic types are produced, all of which are obtained from different processes, using different mixes of chemicals. Therefore, the construction of a complete material balance of all plastic types would be very complicated, whereas data collection on all processes involved would be highly time-consuming. However, the largest part of plastic use is formed by a limited number of different plastics. Therefore, in our analysis only these so-called bulk-plastics are taken into account: polyethylene (PE), subdivided into high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low density polyethylene (LLDPE), polyethylene (PP), polystyrene (PS) and polyvinyl chloride (PVC). Together these plastic types encompass 69% of total plastics consumption in Western Europe (APME, 1996).

Plastics are finally consumed in the form of plastic products. In Table 1 final plastics consumption is subdivided between the plastic products that are discerned in the STREAMS method. Because the STREAMS method is not able to assign all plastics used to plastic products (see Chapter 3), Table 1 also includes primary plastics. These primary plastics are consumed as plastic products of which the shape is unknown.

Our analysis has some resemblance to lifecycle analysis (Heijungs *et al*., 1992). Lifecycle analysis (LCA) implies analysis of all possible environmental impacts of specific products or services throughout their entire lifecycle. In our analysis we do not focus on one product but on the whole final plastics consumption of a country in a specific year. Another difference lies in the fact that an LCA aims at investigation of all environmental issues, whereas our analysis confines itself to material consumption, energy consumption and CO_2 emissions.

Because a LCA focuses on environmental impacts of a specified product, time plays no role: the product is followed from cradle to grave, adding up all environmental impacts during its whole life. This means that environmental impacts from the production of that product are added to environmental impacts of waste management, taking place when the product is discarded after the period of use. The moment of production and the moment of discarding may lie many years apart. In our analysis this procedure would be problematic. Material and energy recycling processes influence material and energy use in other parts of the plastics lifecycle. For example, if more plastics are recycled via mechanical recycling, less primary plastics need to be produced. This means that the processing of discarded (‘old’) materials influences the environmental impacts of the production of ‘new’ materials. If we would follow the LCA approach, future waste management would influence current production in our calculations. In reality, materials that are currently consumed become waste at some point of time in the future. Recycled materials from this future waste cannot influence current materials production. Instead, recycled materials from waste that is currently processed (from products produced in the past) influence current materials production. Therefore, we analyse current waste management, accepting the fact that this concerns products from the past and not the products that are currently produced.

5.2.3 Construction of the material balance

In our method the lifecycle of plastics is represented by a material balance, which shows the annual flows of materials between the processes that are involved. An important feature of a material balance is the fact that for each process the total input of materials equals the total outputs (products and waste). The material balance is constructed from data on the final consumption of plastics and data on the inputs and outputs of materials per unit of product of the processes that are involved. Starting from the data on the final consumption, all materials needed to produce this amount of plastics are calculated stepwise, as is shown in Figure 1 by the dotted lines.

All blocks in Figure 1 concern groups of processes, like processes for producing alkenes or processes for producing polymers. Each group consist of a number of processes. The total materials flow through a group of processes is subdivided between the processes of that group. The shares of material flows through processes in a group are determined by specific demands of the processes one step further in the lifecycle. In other words, the shares of processes in each group are linked to the shares of processes in the group one step further in the lifecycle. For a number of groups this link is quite obvious. For some other groups this link is less obvious. Especially the links between plastic products (final consumption) and processes used to produce these products (plastics processing) and between plastic processing and plastic types (polymers production) are rather difficult to assess. The first link is problematic because it is not always clear which processes are used to manufacture the products that are falling into the product categories defined by Statistics Netherlands (CBS). For example, from one figure on the amount of products used in the category ‘films and sheets’ it is impossible to read the shares of film extrusion and sheet extrusion respectively. A product category ‘plastic school and office supplies’ is even harder to interpret. In these cases we make estimates on the shares of specific processes to produce certain product categories, taking into account the (total) shares of processes used in the plastics processing industry, as derived from (K+R, 1993). The estimated shares are shown in Table 2. The last rows of Table 2 shows that our estimates compare well to available statistical data (K+R, 1993).

Table 2 Estimated shares of plastic processing processes applied to the plastic products that were finally consumed in The Netherlands in 1990

	tube / profile extrusion	**film extrusion**	**blow moulding**	**injection moulding**	**thermoforming[c]**	**rotation moulding**	**foaming**
Plastic building materials	50%			50%			
Plastic industrial semi-finished products	40%			60%			
Plastic films and sheets, cellular							100%
Plastic films and sheets, reinforced		100%					
Plastic films and sheets, others		100%					
Plastic tubes	100%						
Plastic rods and profiles	100%						
Plastic floor covering		50%					50%
Plastic furniture				100%			
Plastic lighting	30%			70%			
Plastic packaging		34%	31%	30%	17%	3%	3%
Refuse bags		100%					
Adhesive tape		100%					
Plastic office and school supplies	45%			55%			
Other plastic products	45%			55%			
Total final plastic products consumption[a]	**29%**	**32%**	**9%**	**24%**	**5%**	**1%**	**6%**
Processes used in the plastics industry[b]	***27%***	***33%***	***8%***	***25%***	***5%***	***2%***	***5%***

[a] Calculated from the final consumption of plastic products (Table 1) and shares of plastic processing processes applied to each plastic product (Table 2); [b] For comparison, calculated from (K+R, 1993); [c] Thermoforming is applied to prefabricated sheets, so two subsequent processes are needed to produce thermoformed products. (Therefore the sum of the rows 'plastic packaging'and 'total final plastic products consumption' exceeds 100%).

A similar problem plays a role in assessing the link between plastic processing and plastic types. Generally, specific processes can be applied to several plastic types. The shares of plastic types used for a specific process are thus variable. The exact shares are the sum of the procedures of a large number of plastics processors, each producing its typical products. In (K+R, 1993) an overview of processes applied to each plastic type is given. Because in that publication processes are collected in groups (all extrusion processes, for example, are collected in one group), additional estimates are needed to connect the processes discerned in our calculations to the plastic types they are applied to. Shares used in our calculations are shown in Table 3. The last rows of Table 3 show that the shares of plastic types in total plastics processing, needed to produce the plastic products that are finally consumed in The Netherlands, are comparable to the shares of plastic types in plastic processing in Western Europe (APME, 1996).

Table 3 Estimated shares of plastic types used in plastic processing processes in The Netherlands in 1990

	(L)LDPE	**HDPE**	**PP**	**PS**	**PVC**
Tube / profile extrusion	5%	12%	10%	21%	51%
Film extrusion	68%		9%		23%
Blow moulding	1%	51%	19%		29%
Injection moulding	8%	12%	47%	23%	11%
Thermoforming				72%	28%
Rotation moulding		100%			
Foaming				100%	
Total final plastic products consumption[a]	**25%**	**11%**	**19%**	**17%**	**28%**
Plastics use in plastics processing[b]	***26%***	***9%***	***17%***	***18%***	***29%***

[a]Calculated from (total) shares of processes (Table 2) and shares of plastic types used per process (Table 3); [b]For comparison, calculated from plastics use in plastics processing in Western Europe (APME, 1996)

5.2.4 Calculation of total lifecycle energy consumption and CO_2 emissions

In Chapter 4 we describe the results of an extensive literature study on energy use, CO_2 emissions and costs of all processes in the plastics lifecycle[6]. We added the results of this study to the method in order to calculate total lifecycle energy consumption, CO_2 emissions and costs.

In our analysis we discern first and second order energy use. First order energy use consists of the energy used for the processes in the plastics lifecycle, including energy for electricity and steam production. Second order energy use includes energy needed for fuels production (fuels used as energy source for the processes in the plastics lifecycle and for electricity and steam production). We also discern first and second order CO_2 emissions. First order CO_2 emissions concern emissions from the processes in the plastics lifecycle and from the production of electricity and steam. Second order CO_2 emissions include emissions from the production of fuels. For a more detailed description of the methodology for calculating first and second order energy use and CO_2 emissions see the appendix to Chapter 4.

One way to reduce fossil feedstock use for plastics is the use of processes that convert biomass into plastic feedstocks. In LCA calculations it is generally accepted that CO_2 emissions from biomass combustion are not accounted for, provided that the biomass used stems from durably harvested crops (IPCC, 1996). We apply this procedure. However, this means that CO_2 emissions from incineration (or gasification) of plastic waste originating from

[6]Although the final plastics consumption of 1990 is taken as basis of the study, the most recent process data is used to describe the processes, because the results of the calculations are used to provide suggestions for future changes in the lifecycle of plastics.

plastics produced from biomass have to be excluded too. We did this by multiplying the amount of CO_2 emissions from plastic waste combustion by the share of plastics produced from fossil feedstocks (excluding plastics from biomass) to total plastic production (including plastics from biomass).

With respect to plastics, material use and energy use are equivalent, because both material and energy are derived from fossil fuels. From one hand this is a favourable feature for the method, because material use and energy consumption can be added and represented in one figure. From the other hand it is rather difficult to make a strict division between fossil feedstocks used as material and fossil fuels used as energy sources. Some processes, like naphtha cracking, produce a number of fuels as by-products, which are used to fire the cracking process. This means that fossil feedstocks that were originally intended to be used as feedstock (in the form of naphtha) are finally used as energy source. Therefore, in the method feedstock consumption is corrected for fuels production[7].

The introduction of plastic waste gasification introduces the production of hydrogen as an important by-product. This implies that less hydrogen has to be produced with conventional processes in order to fulfil society's hydrogen needs. It also implies that less natural gas is needed for hydrogen production. The method takes this into account. A similar aspect plays a role with blast furnace injection. Normally, coal or fuel oil is injected in blast furnaces as a reducing agent. Plastic waste injected in blast furnaces substitutes part of this fuel oil. The method accounts for the avoided fuel oil consumption.

5.2.5 Costs calculation

For all processes in the plastics lifecycle the associated costs (per tonne of product) are assessed based on data from literature. Total costs are subdivided into investments (including contingencies and offsite costs), fixed costs (labour and material costs for maintenance), energy costs and other variable costs (including labour costs for operation and costs of catalysts and chemicals)[8]. Total annual costs per tonne capacity are calculated using the formula:

$$TC = \alpha * I + FC + EC + OVC$$

with TC = Total annual costs, I = Investments, FC = Fixed annual costs, EC = Annual energy costs, OVC = Other variable costs per year, whereas α follows from:

[7] Even if these fuels are not used for the cracking process, the same issue plays a role. In the model, fuels produced as by-products are considered as energy outputs.

[8] For a number of processes only total costs were found. In these case no division is made between investments, fixed costs and variable costs.

$$\alpha = \frac{r}{1-(1+r)^{-L}}$$

with r = rate of interest (in this study taken at 6%) and L = lifetime (in this study 25 years for all chemical processes and 10 years for plastic processing processes).

Energy costs are calculated from the consumption of energy carriers using the energy prices as shown in Table 4.

Table 4 Energy prices used for energy costs calculation

Energy carrier	**Price** [ECU / GJ]
Crude oil[a]	2.6
Fuel oil[b]	2.8
Natural gas[c]	3.2
Electricity[d]	15.7
Steam[e]	3.5
Biomass[f]	3.8

[a]Based on world market prices, mean value for 1990-1998, in which period the market price varied between 2.1 ECU / GJ (1998) and 3.4 ECU / GJ (1990) (CBS, 1998); [b]Calculated from the price of crude oil, including the costs of distillation; [c]Large consumer prices for The Netherlands, mean value for 1991-1998 in which period the natural gas price increased from 2.8 ECU / GJ (1991) to 3.6 ECU / GJ (1998) (Eurostat, 1992-1998) ; [d]Large consumer prices for The Netherlands, mean value for 1991-1998 in which period the electricity price varied between 13.9 ECU / GJ_e (1992) and 16.7 ECU / GJ_e (1995-1996) (Eurostat, 1992-1998); [e]Calculated from fuel oil and natural gas prices, assuming 85% efficiency and 50% steam production from fuel oil and 50% from natural gas; [f]Calculated for poplar / miscanthus, including land, labour and energy costs (Faaij, 1997)

5.2.6 Efficiency Improvement Opportunities

The method is used to analyse the possible effects of options for energy and material efficiency improvement and CO_2 emission reduction. This is done by changing the shares of processes applied to the materials in specific stages of the lifecycle. As explained in paragraph 5.2.3, each block in Figure 1 concerns a stage of the lifecycle that consists of a group of processes, each of which is used to process part of the material flow that runs ‘through’ that stage. Shifts between processes mean changes in the shares of the individual processes of a stage. In each stage shifts can be made by exchanging existing processes or by introducing new processes.

In principle shifts between processes can be made in all blocks discerned in Figure 1. The most “powerful” alternative processes (*i.e.* processes that have a large impact on energy use and emissions), either existing or in development, are in *alkenes production*, *polymers production* and *plastic waste management*.

Apart from the processes to produce alkenes that are currently used (steamcracking of naphtha, gas oil, LPG and ethane), a number of processes are currently under development: oxidative coupling of natural gas, the methanol-to-olefins process (using methanol from natural gas or from biomass) and flash pyrolysis of biomass. In the future these processes may largely change the material balance of plastics production. Therefore they are promising candidates to be deployed in order to reduce the total consumption of fossil energy carriers and feedstocks in the lifecycle of plastics.

With respect to plastics processing, alternative mixes of plastics to be used may contribute to a decrease of fossil feedstock and fuels consumption. For many plastic applications different plastic types can be used. This indicates that certain margins exist with respect to the shares of the different plastics types that are used. The method is used to calculate the effects of changes between plastic types on fossil feedstocks and fuels consumption, CO_2 emissions and costs.

A third potentially powerful way of influencing the material balance is the use of alternative processes for plastic waste management. A larger share use of recycled materials decreases the amount of virgin materials needed. In this study we analyse the effects of shifts between plastic waste management processes that are already commonly used (landfilling, incineration, mechanical recycling) and shifts to 'new' processes: blast furnace injection, gasification, hydrogenation, pyrolysis and selective dissolution[9].

We use the method to assess the effects of shifts between processes for alkenes production, between plastics types that are used and between plastic waste management processes. First we calculate the total consumption of fossil fuels and feedstocks, as well as the CO_2 emissions and costs that are related to the base case. The base case exists of the 1990 situation, with respect to shares of processes and plastic types used. Subsequently we increase the share of a specific process in a specific stage of the plastics lifecycle, simultaneously proportionally decreasing the shares of the other processes of that stage. The method accounts for all changes in the lifecycle that result from this shift and calculates the total consumption of fossil fuels and feedstocks, the CO_2 emissions and the costs of the reduction case.

[9] Because of large differences in contamination between post consumer waste on the one hand and production and processing waste, different mixes of plastic waste management processes are applied to these streams. In the base case a relatively large part of plastic production and processing waste (56%) is mechanically recycled (CBS, 1992) compared to post consumer plastic waste (11%) (APME, 1994). So for a large part of plastic production and processing waste already a satisfying processing route is used. Therefore our calculations only concern alternatives for post consumer waste management, keeping constant the mix of processes for production and processing waste management. For the same reason, while increasing the shares of specific processes for post consumer plastic waste management, shares of all other processes are decreased EXCLUDING mechanical recycling, which is fixed at 11%.

5.2.7 Sensitivities

The results of the aforementioned calculations show that the total consumption of fossil fuels and feedstocks, the total CO_2 emissions and the total costs change approximately linearly with an increasing share of specific processes. Therefore, marginal increases (or decreases) in the total consumption of fossil fuels and feedstocks consumption, CO_2 emissions and costs can be calculated, which show the sensitivities of the plastics lifecycle to a shift to a higher share of specific processes. Sensitivities can be used to weigh the effects of an increased or decreased use of different processes. By focussing on sensitivities we avoid the inclusion of implicit subjective estimates of application potentials in the results. After calculation of the sensitivities they can be used to assess the reduction potentials that are connected to different scenarios reflecting explicit assumptions for the application of specific processes.

A sensitivity is defined as the ratio between the relative change of the calculated value (total material consumption, total energy consumption, total CO_2 emissions or total costs) and the percentage of materials or products to which the measure is applied:

$$Sensitivity(i, j) = \frac{relative\,change\,of\ calculated\,value(i, j)}{application\ percentage(j)}$$

with:

i = *materials consumption, energy consumption, CO_2 emissions or costs*

and:

j = *specific measure*

Sensitivities are to be interpreted as follows: A sensitivity of, for example, CO_2 emissions of a value y [-] means: if the share of the specific process is increased by x%, total lifecycle CO_2 emissions increase by x*y%.

In this study we calculate the sensitivities of the lifecycle of plastics for all processes for alkenes production, for the production of all plastic types, and for all plastic waste management processes.

5.3 Process descriptions

In this section we present the results of a study on the specific energy requirements, CO_2 emissions and costs (per unit of product) of all processes in the lifecycle of plastics.

In Chapter 4 we have analysed the energy use and CO_2 emissions of all processes in the Western European plastics lifecycle in 1994. For the current study on the plastics lifecycle in

The Netherlands in 1990 we use the same energy and CO_2 data. Differences in system boundaries are not expected to lead to large inaccuracies. Nearly all plastics that are finally used in The Netherlands originate from Western Europe. Furthermore, structural changes to the processes in the plastics lifecycle, which generally are highly capital intensive, take place on a much longer time span than the period of four years between 1990 and 1994.

In order to allow the investigation of alternative routes for plastics producing and plastic waste management, in this study a number of new processes is added. These new processes are investigated in paragraphs 5.3.1 to 5.3.3. In paragraph 5.3.4 a summary is given of the energy and CO_2 data of all processes included in the method. In paragraph 5.3.5 this data set is extended with data on process costs.

5.3.1 Feedstock production and processing

The new processes for alkenes production that are described in paragraph 5.3.2 (the Methanol-To-Olefins process and biomass flash pyrolysis) require the 'new' feedstocks methanol and biomass. The production of these feedstocks is analysed in this paragraph.

Biomass production

Using the flash pyrolysis process described in paragraph 5.3.2, biomass is converted into petrochemical feedstocks. There are several biomass flows that can, in principle, be used. These flows are divided between biomass waste flows, arising, for example, from forestry, agriculture, construction and demolition, and dedicated biomass crops. Several biomass crops may be used. Fast growing crops, however, like eucalyptus, miscanthus and poplar, have good chances to be used (Gielen *et al.*, 1998). Biomass crops need land to be produced, which may be a limiting factor for biomass production (Faaij, 1997). Whether or not biomass can be used for petrochemicals production is uncertain, because other options, like electricity production, are competing applications for the biomass.

According to Gielen *et al.* (1998) energy use for biomass growing and harvesting amounts to 0.03 GJ diesel per GJ for miscanthus and 0.04 GJ diesel per GJ for poplar, corresponding to approximately 0.45 GJ per tonne biomass and 0.60 GJ per tonne biomass respectively. For our calculations we use the mean value of 0.53 GJ / tonne dry matter of biomass.

Methanol production

The Methanol-To-Olefins process, described in paragraph 5.3.2, uses methanol as feedstock. Conventional methanol production runs via steam reforming of natural gas, followed by methanol synthesis. Alternatively, methanol can be produced by biomass gasification,

followed by methanol synthesis. Katofsky (1993) studied both process routes in detail. His data are summarised in Table 5. Both processes are exothermic, which accounts for the low energy use.

Table 5 Inputs, outputs, energy requirement and CO_2 emissions of methanol production from natural gas and biomass (Katofsky, 1993)

	Unit	Methanol from natural gas[f]	Methanol from biomass[e]
Inputs:			
Natural gas	[t]	0.56	
Biomass feedstock, dry[c]	[t]		1.68
Process water	[t]	0.95	
Electricity	[GJ_e]	0.32[a]	0.36
Outputs:			
Methanol	[t]	1.0	1.0
CO_2	[t]	0.16[b]	0.28[d]

[a]Net electricity use; Gross energy use: 1.18 GJ_e/t, 0.79 GJ_e of which are produced from waste heat from the process; [b]Net CO_2 production, combined result of CO_2 addition (0.32 t/t methanol) and CO_2 production (0.48 t/t methanol, excluding CO_2 emissions from fuels combustion); [c]10% moisture; [d]Not included in the calculations, because originating from biomass; [e]BCL indirectly heated gasifier; [f]Conventional steam reforming with CO_2 addition

5.3.2 Alkenes production

With respect to the production of alkenes we add three new processes that are may be used in the nearby future: oxidative coupling of natural gas, the methanol-to-olefins process (MTO) and flash pyrolysis of biomass.

Oxidative coupling of natural gas

This process converts methane into valuable products, of which ethylene and propylene are the most important. The process consists of two steps: First methane reacts, with the aid of a catalyst, with pure oxygen into ethylene, ethane, propylene and propane. Furthermore, CO and CO_2 are formed as by-products. In the second step, a conventional ethane cracker, ethane is cracked into ethylene and small amounts of propane, propylene, a C4 fraction, pyrolysis gasoline and hydrogen. In the separation section, non-reacted methane and ethane are separated and recycled to the first and second reactors respectively.

Important features of the methane conversion step are the methane conversion rate (the share of methane that is converted in a single pass) and the C_{2+} selectivity (the share of the higher

hydrocarbons (2+) in the product mix). The yield of hydrocarbons in a single pass trough the reactor (C_{2+} yield) is calculated as the product of methane conversion rate and C_{2+} selectivity. The process has the peculiarity that increasing the methane conversion rate results in a decrease of the C_{2+} selectivity. Therefore, the single pass C_{2+} yield is limited. Before the introduction of membrane reactors, many catalysts have been investigated without, however, reaching single pass C_{2+} yields over 10% (Kaddouri *et al.*, 1989). Membrane reactors show higher C_{2+} yields than conventional fixed bed reactors (Miguel *et al.*, 1996). With membrane reactors, in which oxygen can be distributed very evenly, methane conversion rates of 20-30% have been achieved so far, with a C_{2+} selectivity of up to 80 mol%. With a methane conversion rate of 20%, this corresponds to a C_{2+} yield of 16% (Cordi *et al.*, 1997). Although model calculations predict that with membrane reactors a single pass C_{2+} yield of about 50% should be possible (Lu *et al.*, 1997), C_{2+} yields in experiments have not yet exceeded 20% (Miguel *et al.*, 1996). An upper bound of the C_{2+} yield of about 30% has been argued based on the reaction mechanism considerations (Parkyns *et al.*, 1993). From different publications it can be derived that a combination of a methane conversion rate of 30% and a C_{2+} selectivity of 80-85% is a feasible assumption to be reached in the nearby future (Van Geem, 1992), (Geerts *et al.*, 1992), (Amenomiya *et al.*, 1990). This corresponds to a single pass C_{2+} yield of 24-26%.

Because of the relatively low conversion rates achieved, the process involves extensive recycling streams. This affects both investments and energy use for product separation. Membrane separation could be a future means to reduce energy consumption. However, much research has still to be done in this field. So in the nearby future (up to around 2020) membrane separation is not expected to be available (Gielen *et al.*, 1996). Therefore we do not model membrane separation in this study.

For our calculations we use data from studies by Van Geem (1992) and Geerts *et al.* (1992). Both start from a methane conversion rate of 30% and a C_{2+} selectivity of 80-85%. Table 6 shows the product composition of the methane conversion step (Van Geem, 1992).

Table 6 Product composition of the methane conversion step of oxidative coupling (Van Geem, 1992)

	Product composition [mol%]
Ethylene	50
Ethane	30
Propylene	1-2
Propane	3-4
CO	5
CO_2	10

From this product composition and the partial oxidation reaction equations the amount of oxygen needed and the amount of steam formed can be calculated. The results are used to

complete the material and energy balances, which are shown in Table 7. Ethylene, propylene, C_4 and pyrolysis gasoline are regarded as valuable products; carbon monoxide, propane, methane and hydrogen as fuels.

Table 7 Material and energy balance of oxidative coupling of methane, including ethane cracking (see Chapter 4)

	Input	**Output**	**Input**	**Fuels output**[a]	**Products output**	**Total output**
	[tonne]	[tonne]	[GJ]	[GJ]	[GJ]	[GJ]
Methane	1.43		71.6			
Oxygen	1.48					
Ethylene		1.00			47.2	
CO		0.07		0.7		
CO_2		0.21				
Propane		0.07		3.2		
Propylene		0.04			1.9	
H_2O		1.46				
C_4		0.01			0.6	
Pyrolysis gasoline		0.01			0.2	
Methane		0.03		1.6		
Hydrogen		0.02		2.9		
Total	**2.91**	**2.91**	**71.6**	**8.3**	**50.0**	**58.3**

[a]Gross fuels output, including fuels that are internally combusted in the ethane cracking step

From Table 7 it can be seen that the process is exothermic. The net reaction energy surplus of both processes together amounts to 13.3 GJ per tonne ethylene. It is the combined result of the reaction energy surplus of the methane conversion step of 15.0 GJ per tonne ethylene and the reaction energy demand of the ethane cracker of 1.7 GJ per tonne ethylene. According to Geerts *et al.* (1992), the process produces 8.8 GJ of high pressure steam, which can be used for electricity production. This figure is lower than the 13.3 GJ from the energy balance, because the process itself needs energy for compression.

According to Geerts *et al.* (1992), the net production of fuel gas amounts to 5.6 GJ. per tonne ethylene. Process energy requirement amounts to 2.85 GJ fuels per tonne ethylene[10] (Van Geem, 1992), for which part of the output fuels are used. So the total deliverance of fuels amounts to 8.45 GJ. This figure is in keeping with the gross fuels output of 8.3 GJ. per tonne ethylene from the energy balance (Table 7). Furthermore, the process needs 55 kWh of electricity per tonne ethylene produced (Van Geem, 1992). Table 10 summarises the data that are used for the calculations.

[10] CO_2 emissions from combustion of these fuels produced in the process are included in the CO_2 emissions indicated in the datasheet, together with the CO_2 emissions from the process itself

Methanol to olefins (MTO)

The Methanol-to-olefins (MTO) process runs via catalytic dehydration of methanol. The reaction takes place at temperatures between 350 and 500°C (Schönfelder *et al.*, 1994b) and a variety of catalysts can be used. Experiments show that the product composition of the process is highly dependent on the catalyst used (Van Geem, 1992), (Redwan, 1997), (Schönfelder *et al.*, 1994a). Most MTO processes are designed to maximise ethylene yield. It is, however, possible to reach very high propylene yields instead (Schönfelder *et al.*, 1994a), (Chen *et al.*, 1994). To a lesser degree, the product output can be influenced by changing the reaction temperature, which influences the reaction severity (ethylene/propylene ratio). For example (HCP, 1997) describes a MTO plant of which the ethylene to propylene ratio can be varied between 1.2 and 1.5 by altering the reaction temperature. Current catalysts show a methanol conversion rate of 100%. The MTO process is currently ready to be implemented. In Hydrocarbon Processing (1997) a MTO process is presented, which is commercially available.

Van Geem (1992) gives specifications of different MTO plants, working at different severities. According to Van Geem (1992) processes with high propylene co-production are the most economically feasible. Therefore, we take the MTO process with the highest severity (the so-called IFP process) as representative. The material and energy balances of this process are given in Table 8. Ethylene, propylene and the C_4 fraction are considered as commercial products, the rest as fuels. The fuels are used for the process itself.

According to Stratton *et al.* (1983), the energy consumption of the Mobil MTO process amounts to 11.6 GJ per tonne ethylene produced. The Mobil process, however, has a different product distribution than the IFP process. It uses 4.52 tonne methanol feedstock per tonne ethylene produced (Stratton *et al.*, 1983), whereas the IFP process uses 5.98 tonne methanol feedstock (Van Geem, 1992). This is due to the larger propylene production of the IFP process. The higher feedstock throughput of the IFP process affects its energy consumption. We scaled the energy requirement using the ratio of the feedstock inputs required. This way, the energy consumption of the IFP process is estimated at 12.3 GJ per tonne ethylene produced. In this figure we include an estimated energy efficiency improvement of 20% since the year of publication (1983)[11]. The process produces 9.5 GJ of fuels per tonne ethylene, so 2.8 GJ of extra fuels have to be added to run the process.

According to Stratton *et al.* (1983), the Mobil process needs 2.7 GJ of energy for compression per tonne ethylene produced. If scaled to the feedstock input of the IFP process this means an energy consumption for compression of 3.6 GJ. The process is exothermic (see Table 8).

[11] This estimate is based on the comparable historical energy efficiency improvement of ethane crackers, as observed by Steinmeyer (1997)

From the energy balance it can be seen that it produces 2.5 GJ of steam, which can be used for compression. However, 1.1 GJ of steam have to be added to fulfil the energy demand for compression. According to Van Geem (1992), the Union Carbide MTO process needs 55 kWh electricity per tonne ethylene produced (feedstock input is 4.3 tonne methanol per tonne ethylene). Scaled to 5.98 tonne methanol input, we calculate an electricity input of 75 kWh per tonne ethylene for the IFP process.

CO_2 emissions are calculated from the combustion of the process output fuels. In order to avoid double counting, CO_2 emissions caused by the combustion of the extra fuels needed are excluded. In our method these CO_2 emissions are calculated from fuels consumption. The data used in the calculations are summarised in Table 10.

Table 8 Material and energy balances of the IFP methanol-to-olefins process

	Material balance[a] [t/t ethylene]	**Energy balance** [GJ/t ethylene]
Inputs:		
Methanol	**5.98**	**126.2**
Outputs:		
Products:		
Ethylene	1	47.2
Propylene	1.11	50.8
C_4	0.36	16.3
Total	**2.47**	**114.2**
Fuels:		
Methane	0.07	3.6
Ethane	0.01	0.3
Propane	0.09	4.3
C_{5+}	0.03	1.3
Total	**0.20**	**9.5**
Water:	**3.31**	
Total output	**5.98**	**123.7**
Energy requirement:		**12.3**
Extra fuels needed:		**2.8**

[a](Van Geem, 1992)

Biomass (flash) pyrolysis

There are several approaches to convert biomass into valuable hydrocarbons including olefins. With the so-called flash pyrolysis process biomass is cracked at high temperatures (about 1000°C) into ethylene, BTX, carbon monoxide and carbon dioxide (Steinberg *et al.*, 1992). Paushkin *et al.* (1994) propose another route, consisting of three steps: steam gasification at 1000-1200°C, resulting in a mixture of carbon monoxide, carbon dioxide and hydrogen, followed by synthesis of hydrocarbons and catalytic pyrolysis at 790°C. This way,

1.5 tonne olefins could be obtained from 10 tonnes of biomass. However, little information on this process is available. Because more processing steps are needed than with the flash pyrolysis process, which probably leads to higher energy demand and investment costs, we do not consider this process as a valuable option, but analyse the flash pyrolysis process. In 1992 a pilot flash pyrolysis plant was in operation in Canada (Steinberg *et al.*, 1992). Therefore we estimate that the process becomes commercially available in about 2010.

For the flash pyrolysis process an entrained down flow reactor is used. It is necessary to keep the reactor residence time short (1 second) in order to prevent unwanted secondary reactions. Steinberg *et al.* (1992) found that pyrolysis in the presence of methane considerably increases hydrocarbon yields. Methane plays a role in the pyrolysis process, but it is not cracked. It is recovered from the product stream and recycled. The type of biomass used influences the product distribution of the process. Steinberg *et al.* (1992) found that the ethylene yield varies between 20.7% and 27.4% for fir and pine wood pyrolysis respectively, both with methane addition. For our study we calculate the product distribution as the mean between fir and pine wood pyrolysis, based on data from Steinberg *et al.* (1992). The result is shown in Table 9. Ethylene and BTX are regarded as valuable products, carbon monoxide and ethane as fuel. The process also produces some char and ashes.

Table 9 Product distribution of biomass (flash) pyrolysis with methane at 1000°C (Steinberg *et al.*, 1992). Figures refer to carbon content conversion.

	Fir [%]	**Pine** [%]	**Mean** [%]
Ethylene	20.7	27.4	24.1
BTX	12.7	24.6	18.7
CO	48.1	38.7	43.4
CO_2	3.3	2.7	3.0
Ethane	2.0	0	1.0

Assuming a carbon content of wood of 50% (Gielen *et al.*, 1996), it is calculated that 8.3 tonnes of biomass are needed for each tonne of ethylene that is produced. Gielen *et al.* (1996) estimate that, for delivering the process energy use, another 3.5 tonnes (52.5 GJ) of biomass are needed. The flash pyrolysis process has much in common with the naphtha cracking process. Therefore we adapt electricity requirement data from the naphtha cracking process (see Chapter 4), which we scale according to feedstock input (8.3 tonne biomass per tonne ethylene versus 3.3 tonne naphtha per tonne ethylene).

We assume that the process delivers enough high pressure steam to drive the compressors (which is also the case with naphtha cracking). Therefore the electricity demand is relatively low. As can be seen in Table 9, 3.0% of the biomass is converted into CO_2. However, as these CO_2 emissions arise from biomass that is assumed to be produced in a sustainable way, they are not taken into account in the calculations. For the same reason the CO_2 emissions from

biomass combustion for process heat production are not taken into account. Data for the calculations are summarised in Table 10.

Table 10 Inputs, outputs, energy requirement and CO_2 emissions of oxidative coupling of natural gas, the methanol-to-olefins process and flash pyrolysis of biomass

	Unit	Oxidative coupling	MTO	Biomass pyrolysis
Inputs:				
Natural gas	[t]	1.43		
Methanol	[t]		5.98	
Biomass feedstock	[t]			8.3
Oxygen	[t]	1.48		
Fuel	[GJ]		2.8	
Biomass fuel	[GJ]			52.5
Electricity	[GJ_e]	0.20	0.3	0.7
hp-Steam	[GJ]		1.1	
Outputs:				
Products:	**[t]**	**1.06**	**2.47**	**1.78**
Ethylene	[t]	1.00	1.00	1.00
Propylene	[t]	0.04	1.11	
C_4	[t]	0.01	0.36	
Pyrolysis gasoline (BTX)	[t]	0.01		0.78
CO_2[a]	[t]	0.37	0.59	0.12[b]
H_2O	[t]	1.46		
CO	[GJ]			18.3
Ethane	[GJ]			2.0
Propane	[GJ]	3.2		
Hydrogen	[GJ]	2.4		
hp-steam	[GJ]	8.8		

[a]Process CO_2 emissions including CO_2 emissions from internal combustion of output fuels; [b]CO_2 emissions from biomass pyrolysis are not used in the calculations, because stemming from biomass

5.3.3 Plastic waste management

In Chapter 4 we have investigated a number of processes for plastic waste management: landfilling, incineration, blast furnace injection, gasification, pyrolysis, hydrogenation and mechanical recycling (or re-extrusion). For the present study we add one new process: selective dissolution.

Selective dissolution

Selective dissolution is based on the differences in solubility between different polymers. The process is developed by Rensselaer Polytechnic Institute (USA). Before the process can be applied, mixed plastic waste has to be ground, washed and dried. By subsequently bringing the mixed plastic waste into contact with solvents of increasing temperatures (20-150ºC), polymers dissolve one by one. This way, PS, LDPE, HDPE, PP, PVC and PET are subsequently extracted from the mixture of plastics. As solvent xylene or tetrahydrofuran is used. The polymers are recovered from the solvents by 'flash devolatilisation', in which most of the solvent is evaporated. The remaining solvent is removed in an extrusion step, from which the polymers arise as regranulate (Smit, 1993).

Zagouras *et al.* (1995) investigated the economic feasibility of a selective dissolution process that is slightly different. Their process subsequently uses different solvents (hexane, acetone, methylethylketone) to recover the different plastic types. Polymers are recovered from the solution by adding it dropwise to a non-solvent like methanol. This way a suspension is obtained, which is filtrated to recover the polymer. The solvents are recycled. Energy requirement and costs are highly dependent on the amount of solvents needed per tonne mixed plastic waste and the amount of solvents lost. Both parameters have to be investigated yet. Zagouras *et al.* (1995) estimate that a volume of 2200-6600 litres of solvents is needed per tonne mixed plastic waste. They also estimate the percentage of solvents that are lost at 0.1-1%. They calculate energy requirement and costs both for 2200 litres per tonne / 0.1% loss and 6600 litres per tonne / 1% loss, as well as for an 'intermediate case' with values in between. We use the results of the 'intermediate case' as representatives. Data on selective dissolution can be read from Table 11.

Table 11 Inputs, outputs and final energy requirement for selective dissolution of mixed plastic waste

	Unit	Selective dissolution
Inputs:		
Mixed plastic waste	[t]	1.00
Solvents	[t]	0.04
Methanol	[t]	0.04
Electricity	[GJ_e]	1.5
Fuel	[GJ]	4.5
Outputs:		
Regranulate	[t]	0.62
RDF[a]	[GJ]	7.6

[a]Refuse derived fuel (a mixture of contaminations and losses, mainly consisting of paper, wood and 'other plastics'): 0.38 tonne, valued at 20 GJ/ton

5.3.4 Summary of energy- and CO_2-data of processes in the plastics lifecycle

In Table 12 the data on energy inputs, energy outputs and CO_2 emissions of all processes in the plastics lifecycle, as used in the calculations, are summarised. Table 12 brings together the data on the processes investigated in this chapter and those investigated in Chapter 4.

Table 12 Summary of energy and CO_2 data of processes in the plastics lifecycle

	Energy Input					**Energy Output**			**CO_2 emissions[c]**
	Electricity	**Natural gas**	**Fuel oil**	**Steam**	**Internal combustion**	**Electricity**	**Steam**	**Fuels[b]**	**Process CO_2**
	[GJ_e/t]	[GJ/t]	[GJ/t]	[GJ/t]	[GJ/t]	[GJ_e/t]	[GJ/t]	[GJ/t]	[t/t]
Crudes extraction and feedstock production:									
Crude oil extraction and transport			1.0						
Natural gas extraction and transport	1.1	0.1							
Crude oil distillation	0.0		1.9	0.1					
Biomass production			0.5						
Methanol from natural gas	0.3								0.16
Methanol from biomass	0.4								-[g]
Alkenes production:									
Ethane steamcracking[a]	0.1		1.8		12.3			12.3	0.23
LPG steamcracking[a]	0.2				10.9			21.0	0.60
Naphtha steamcracking[a]	0.1				8.7		0.3	13.2	0.48
Gas oil steamcracking[a]	0.1				9.3		0.5	21.5	0.46
Oxidative coupling of natural gas[a]	0.2				2.7		8.3	5.3	0.35
Methanol to olefins[a]	0.1		1.1	0.5	3.9			3.9	0.24
Biomass flash pyrolysis[a,d]	0.4							11.4	-[g]
Intermediates production:									
Benzene	0.1		1.0	1.8					
Styrene	0.3		4.9	5.1			4.8		
VCM	0.3		4.3	5.3					
Polymers production:									
LDPE liquid phase	3.1						0.4		
LLDPE gas phase	2.0			0.3					
LLDPE solution / suspension	1.7			1.6					
HDPE gas phase polymerisation	2.0			0.3					
HDPE solution / suspension	1.7			2.0					
PP liquid phase	2.1			1.2					
PP gas phase	2.1			0.8					
PP suspension	2.1			1.8					
PS	0.7		0.2	1.5					

	Energy Input					Energy Output			CO_2 emissions[c]
	Electricity	Natural gas	Fuel oil	Steam	Internal combustion	Electricity	Steam	Fuels[b]	Process CO_2
	[GJ_e/t]	[GJ/t]	[GJ/t]	[GJ/t]	[GJ/t]	[GJ_e/t]	[GJ/t]	[GJ/t]	[t/t]
PVC	1.0		0.7	2.8					
Plastic processing:									
Film extrusion	1.9								
Thermoforming	12.6								
Blow moulding	2.2								
Injection moulding	5.2								
Rotation moulding	1.4	16.0							
Foaming	0.4	1.0							
Tubes / profiles extrusion	1.4								
Auxiliary materials:									
Oxygen	1.0								
Chlorine	5.9			2.7					
Hydrogen[e]	2.0	47.3							4.62
Plastic waste management[f]:									
Landfilling			0.1						
Incineration without heat recovery									2.88
Incineration with heat recovery						7.6			2.88
Upgrading to mixed plastic waste	0.3	0.8							
Blast furnace injection	0.8								
Pyrolysis	1.2	3.9						8.4	
Gasification / hydrogen production	0.9	3.3				0.2			2.77
Hydrogenation	1.8	4.6		0.1				4.8	
Selective dissolution	1.5	4.5						7.6	
Mechanical recycling	2.5								

[a]Per tonne of products (ethylene, propylene, C4, BTX); [b]Gross fuels production, including internal combusted fuels; [c]Process CO_2 emissions, including internal combustion of produced fuels, excluding combustion of other fuels; [d]29.6 GJ Biomass used as fuel; [e]Only used in small amounts for hydrogenation. Hydrogen production is mainly included in the method to allow the calculation of credits for hydrogen production by gasification; [f]Per tonne of plastic waste processed; [g]Not accounted for, because stemming from biomass

5.3.5 Process costs

In our previous study on the Western European plastics lifecycle (Chapter 4) process costs were not investigated. In this paragraph the results are given of an investigation of the costs of all processes in the plastics lifecycle, based on a survey of the literature. In Table 13 costs are divided between investments, fixed costs and variable costs (excluding energy costs). Total

costs are calculated using the formula from paragraph 5.2.5. The results are shown in the column 'Total cost, calculated'. In some cases, only total costs data are given in literature. These total costs from literature are shown in the column 'Total costs, literature'.

Table 13 Cost data of processes in the plastics lifecycle

	Investments [ECU /t]	**Fixed costs** [ECU /t]	**Variable costs**[D] [ECU /t]	**Total costs, literatue** [ECU /t]	**Total costs, calculated** [ECU /t]
Crudes extraction and feedstock production:					
Crude oil extraction and transport[a]				111	
Natural gas extraction and transport[b]				160	
Crude oil distillation[c]	24	0.38	0.01		2
Biomass production[d]				48	
Methanol from natural gas[F]	228	6	4		27
Methanol from biomass[F]	469	12	10		58
Alkenes production:					
Ethane steamcracking[e]	406	12	4		48
LPG steamcracking[e]	284	8	3		33
Naphtha steamcracking[e]	262	8	2		31
Gas oil steamcracking[e,f]	271	8	2		31
Oxidative coupling of natural gas[g,h]	848	44	83		194
Methanol to olefins[e,g]	292	9	6		38
Biomass flash pyrolysis[i]	1225	36	12		143
Intermediates production:					
Benzene[k,l]	25	1	2		5
Styrene[j,k,l]	651	26	19		96
VCM[n,o]	294	10	15		48
Polymers production:					
LDPE liquid phase[m]	668	42	40		135
LLDPE gas phase[m]	337	16	34		75
LLDPE solution / suspension[m]	618	39	33		120
HDPE gas phase[m]	337	14	34		74
HDPE solution / suspension[m]	618	39	33		120
PP liquid phase[p]	951	42	40		157
PP gas phase[p]	951	14	34		123
PP suspension[p]	951	42	43		160
PS polymerisation[q,l]	800	32	34		129
PVC polymerisation[r]	555	25	38		107
Plastic processing:					
All processes[s,l]	875	35	123		277
Auxiliary materials:					
Oxygen[t]	200	10			26

	Investments [ECU /t]	**Fixed costs** [ECU /t]	**Variable costs[D]** [ECU /t]	**Total costs, literatue** [ECU /t]	**Total costs, calculated** [ECU /t]
Chlorine[u]	352	47	42		117
Hydrogen[E,C]	614	15	17		81
Plastic waste management:					
Landfilling[v]				25	
Incineration without heat recovery[w]				53	
Incineration with heat recovery[v]				105	
Upgrading to mixed plastic waste[x]				175	
Blast furnace injection[y]				150	
Pyrolysis[y,z]				300	
Gasification / hydrogen production[y,z]				575	
Hydrogenation[y,z]				375	
Selective dissolution[y,A]	389	16	38		234
Mechanical recycling[l,B]	850	34	81		182

[a]Mean value of world market price during the period 1990-1998. During that period world market prices varied between 90 ECU/tonne (1998) and 128 ECU/tonne (1990, 1996, 1997) (CBS, 1998); [b]Mean value over the period 1990-1998. Natural gas prices for large consumers in The Netherlands have increased from 140 ECU/tonne in 1990 to 180 ECU/tonne in 1998 (Eurostat, 1992-1998); [c](SERUM, 1989); [d](Faaij, 1997), poplar / miscanthus, including land, labour and energy costs; [e](Stratton *et al.*, 1983); [f]Calculated from naphtha and ethane cracking, scaled by dimensions of feedstocks input and recycle streams; [g](Van Geem, 1992); [h](Geerts *et al.*, 1992); [i]Calculated from naphtha steamcracking, scaled by dimensions of feedstock input (biomass pyrolysis: 8.3 t/t ethylene, naphtha cracker: 3.3 t/t ethylene), 25% added to account for the large methane recycle streams of biomass pyrolysis; [j](HCPBC, diverse years); [k](Chauvel *et al.*, 1989a); [l]Fixed costs calculated as 4% of investments; [m](Patel, 1996); [n](Chauvel *et al.*, 1989b); [o](HCP, diverse years); [p]Average investments of six PP plants build between 1990 and 1996 (HCP, 1990-1996), fixed costs and variable costs equal to comparable PE production processes; [q]Investments estimated based on comparable PE/PP liquid phase and suspension polymerisation processes, variable costs: (HCP, 1995); [r]Costs estimated based on specifications of ten different PVC polymerisation plants (HCPBC, 1991-1997); [s]Film extrusion, extrusion coating, sheets extrusion, thermoforming, blow moulding, injection moulding, foaming, tubes extrusion, profiles extrusion, cable extrusion and other plastic processing processes. Estimated average costs for all processes, based on (Tonino, 1996) and (Mulder, 1994). Variable costs estimated at 14% of investments, including 10% labour; [t]Source: MATTER input-data ECN; [u](Gielen, 1997); [v](Faaij, 1997); [w]Estimated as 50% of incineration with heat recovery; [x](Gielen *et al.*, 1994), (Sas *et al.*, 1994); [y]Including 150 ECU/t for preparatory treatment (Dröscher, 1996); [z](Gielen *et al.*, 1994); [A](Zagouras *et al.*, 1995); [B](Sas *et al.*, 1994); [C]hydrogen production from natural gas; [D]Excluding energy costs; [E](Katofsky, 1993)

5.4 Results

In this section the results of the calculations are presented. First, in paragraph 5.4.1, detailed results for the base case are given. Subsequently, in paragraph 5.4.2, the sensitivities of total CO_2 emissions, total fossil fuels and feedstocks use and total costs of the whole plastics lifecycle for changes in the shares of specific processes are presented.

5.4.1 The base case

The base case reflects material flows that were needed to fulfil the final plastics consumption and to process the plastic waste arising in The Netherlands in 1990. With these material flows and data on the associated processes, total energy use, CO_2 emissions and costs of the whole plastics lifecycle have been calculated. The results are shown in Table 14. From Table 14 it can be seen that not all processes incorporated in the method were used in 1990. They are included in order to allow an assessment of potential changes (see paragraph 5.4.2).

Table 14 Material flows, energy use, CO_2 emissions and costs of the base case (based on the Netherlands consumption of plastic products in 1990)

	Material flow [ktonne]	**Net primary energy use[a], 1st order** [PJ]	**Net primary energy use[a], 1st and 2nd order** [PJ]	**Fuels production** [PJ]	**Net CO_2 emissions[b], 1st order** [ktonne]	**Net CO_2 emissions[b], 1st and 2nd order** [ktonne]	**Total costs** [10^6 ECU]
Crudes extraction and feedstock production:							
Crude oil extraction and transport	1248	1.2	1.3		90	109	139
Natural gas extraction and transport	41	0.1	0.1		5	6	6
Crude oil distillation	1248	2.5	2.7		179	216	10
Biomass production							
Methanol from natural gas							
Methanol from biomass							
Total	**1289**	**3.8**	**4.1**		**274**	**331**	**155**
Alkenes production:							
Ethane steamcracking	35	0.5	0.5	0.4	13	14	2
LPG steamcracking	79	0.9	1.0	1.7	48	49	1
Naphtha steamcracking	741	6.4	6.8	9.8	345	346	14
Gas oil steamcracking	145	1.3	1.4	3.1	62	62	0
Oxidative coupling of natural gas							
Methanol to olefins							
Biomass flash pyrolysis							
Total	**1000**	**9.1**	**9.7**	**15.0**	**469**	**471**	**16**
Intermediates production:							
Benzene	158	0.5	0.5		34	39	2
Styrene	198	1.1	1.2		78	95	23
VCM	330	3.6	3.9		244	281	27
Total		**5.3**	**5.6**		**356**	**415**	**53**
Polymers production:							
LDPE liquid phase	212	1.5	1.7		61	81	38

	Material flow	**Net primary energy use[a], 1st order**	**Net primary energy use[a], 1st and 2nd order**	**Fuels production**	**Net CO_2 emissions[b], 1st order**	**Net CO_2 emissions[b], 1st and 2nd order**	**Total costs**
	[ktonne]	[PJ]	[PJ]	[PJ]	[ktonne]	[ktonne]	[10^6 ECU]
LLDPE gas phase	41	0.2	0.2		9	12	4
LLDPE solution / suspension	27	0.2	0.2		8	10	4
HDPE gas phase	15	0.1	0.1		3	4	2
HDPE solution / suspension	118	0.7	0.8		38	46	18
PP liquid phase	69	0.4	0.5		21	26	13
PP gas phase	69	0.4	0.5		19	24	11
PP suspension	69	0.5	0.5		24	30	14
PS polymerisation	194	0.7	0.7		38	45	28
PVC polymerisation	323	2.0	2.2		116	136	43
Total	**1137**	**6.6**	**7.4**		**338**	**414**	**176**
Plastic processing:							
Film extrusion	374	1.7	1.9		73	95	115
Tubes / profiles extrusion	337	1.1	1.3		49	63	101
Blow moulding	101	0.5	0.6		23	30	31
Injection moulding	283	3.5	4.0		151	197	101
Thermoforming	56	1.7	1.9		72	94	26
Rotation moulding	11	0.2	0.2		11	12	4
Foaming	65	0.1	0.1		6	7	19
Total	**1226**	**8.9**	**10.1**		**385**	**498**	**397**
Auxiliary materials:							
Oxygen	44	0.0	0.0		1	1	0
Chlorine	195	1.6	1.8	0.1	74	92	20
Total	**239**	**1.6**	**1.8**	**0.1**	**75**	**94**	**20**
Plastic waste management:							
Landfilling	450	0.1	0.1		5	6	11
Incineration without heat recovery	50				144	144	3
Incineration with heat recovery	231	-4.2	-4.8		483	428	-3
Upgrading to mixed plastic waste							
Blast furnace injection							
Pyrolysis							
Gasification / hydrogen production							
Hydrogenation							
Selective dissolution							
Mechanical recycling	132	0.8	0.9		34	44	29
Total	**863**	**-3.4**	**-3.8**		**665**	**622**	**40**
Grand total		**31.9**	**34.9**	**15.1**	**2562**	**2844**	**857**

[a]Fuels consumption plus electricity consumption plus steam consumption minus electricity production minus steam production; [b]CO_2 emissions from fuels, electricity and steam consumption minus avoided CO_2 emissions from electricity and steam production

From Table 14 it follows that gross feedstocks consumption of the plastics lifecycle amounted to 1284 ktonne of crude oil (lower heating value (LHV) 53.3 PJ) and 41 ktonne of natural gas (LHV 1.6 PJ). Together they have an energy use of 54.9 PJ (LHV). 15.1 PJ of these were converted into fuels as by-products (Table 14), so net feedstock consumption amounted to 54.9 – 15.1 = 39.8 PJ. Energy consumption (1st and 2nd order) amounted to 34.9 PJ (Table 14), so in total 74.7 PJ of fossil feedstocks and fuels (1st and 2nd order) were needed to fulfil the need of plastic products in The Netherlands in 1990.

The results of our calculations can be compared to the results of an energy analysis of plastics production by Worrell *et al.* (1994). They give first order GER (Gross Energy Requirement) values for the production of the different plastics[12]. From these GER values first order fossil energy consumption for plastics production (excluding plastic waste management) is calculated at 75.4 PJ. This comes very close to the first order fossil energy consumption for plastics production that is calculated from Table 14.

Table 14 shows that all stages in the plastics lifecycle contribute to total energy consumption and CO_2 emissions. Waste management has a high share in CO_2 emissions (24%), owing to a relatively large share of waste incineration in the Netherlands waste management system. Because the Netherlands government aims at further increasing the share of incineration, in the future CO_2 emissions from plastic waste management will increase considerably. Table 14 also shows that plastic processing has a high share in total lifecycle costs, because of the high labour intensity and relatively low material throughputs of plastic processing processes.

5.4.2 Improvement cases

This paragraph gives an overview of the calculated sensitivities of the plastics lifecycle for changes in the shares of processes in different parts of the lifecycle. All sensitivities are calculated as the quotient of the change of output value (total fossil feedstocks consumption[13], total fossil fuels consumption[14], total CO_2 emissions[15] and total costs[16]) and change of the share of the process[17]. All changes are calculated relative to the base case.

[12] PE: 69.8 GJ/t, PP: 61.6 GJ/t, PS: 81.5 GJ/t and PVC: 55.7 GJ/t

[13] Excluding feedstocks converted into fuels as by-products

[14] Net 1st and 2nd order primary energy consumption, including internal combustion of produced fuels

[15] Net 1st and 2nd order CO_2 emissions

[16] Including energy costs

[17] Shares of all other processes are decreased / increased proportionally

Alkenes production

In the base case four processes for alkenes production are used: steamcracking of ethane, LPG, naphtha and gas oil. Their shares are 8%, 11%, 69% and 12% of total alkenes production respectively (Chauvel, 1989a). Figure 2 shows the calculated sensitivities of the plastics lifecycle for changes in these shares, as well as for the introduction of the alternative processes: oxidative coupling of natural gas, the methanol to olefins process using methanol produced from natural gas or from biomass, and flash pyrolysis of biomass.

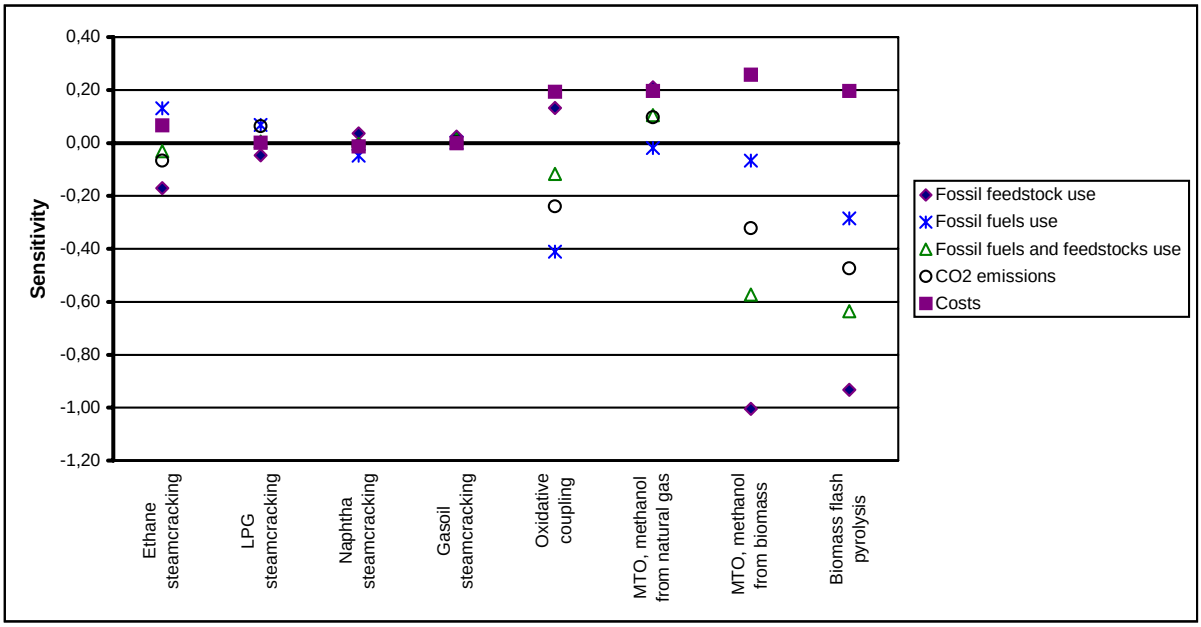

Figure 2 Sensitivities of total fossil fuels and feedstocks use, total CO_2 emissions and total costs of the plastics lifecycle for increases of the shares of specific processes for alkenes production relative to the base case.

Figure 2 shows that changes between steamcracker feedstocks only marginally affect total fossil fuels and feedstocks use, CO_2 emissions and costs of the whole plastics lifecycle. It also shows that the effects of introducing new processes are more extensive. Comparing the four new processes shows that especially the alternatives using biomass are powerful in reducing total fossil fuels and feedstocks use and CO_2 emissions. Oxidative coupling combines modest decreases in total fossil fuels and feedstocks use and CO_2 emissions with a relatively high increase in total costs. The MTO process combined with conventional methanol production performs rather badly: it shows increased costs, increased fossil fuels and feedstocks use and increased CO_2 emissions. The MTO process combined with methanol production from biomass obviously performs much better in terms of energy consumption and CO_2 emissions. Flash pyrolysis of biomass shows the largest reductions of CO_2 emissions and fossil fuels and feedstocks use, however, at substantially higher costs.

Polymers production

In this study the four most extensively used plastic types (PE, PP, PS and PVC) are investigated. In the base case they make up 36%, 18%, 17% and 28% of the whole group respectively[18]. In the left part of Figure 3 the sensitivities of the plastics lifecycle for changes of the shares of these four plastic types are shown. Next the effects of exchanging liquid phase, solution and suspension processes for PE production by the gas phase process are given, as well as the effects of exchanging PE by PP while shares of PS and PVC remain constant (this simulates the current trend towards increased PP use). Finally, the effects of reducing plastic waste from plastics processing, packing and assembling (7.4% in the base case (see Chapter 3)) are shown.

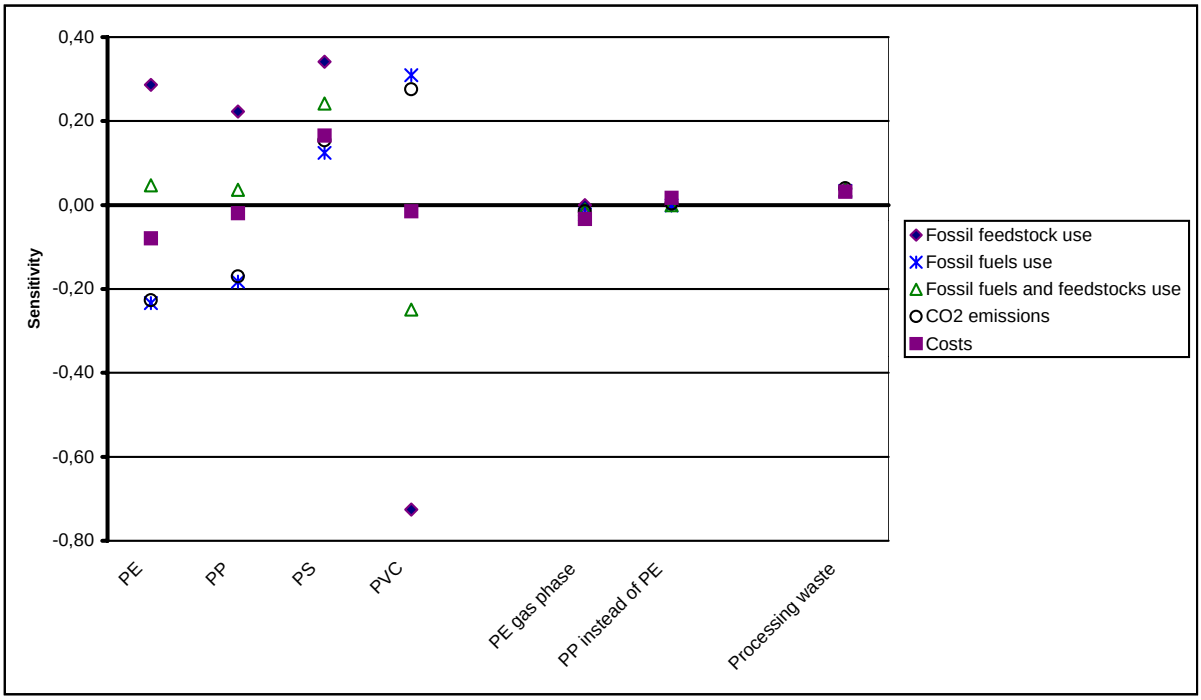

Figure 3 Sensitivities of total fossil fuels and feedstocks use, CO_2 emissions and costs of the whole plastics lifecycle for increases of the shares of plastic types, plastic production processes and processing waste relative to the base case

Figure 3 shows that the use of PS involves the highest fossil fuels and feedstocks use, CO_2 emissions and costs. By increasing the share of PVC fossil feedstocks use is reduced considerably. Although fossil fuels use increases, total fossil fuels and feedstocks use is reduced, but CO_2 emissions are considerably increased and costs are slightly reduced. Figure

[18] These percentages concern the division of plastic types that are incorporated in the plastic products that were finally used in The Netherlands in 1990. They are calculated from the final consumption of plastic products (Table 1), shares of plastic processing processes applied to plastics products (Table 2) and shares of plastic types used in plastic processing processes (Table 3).

3 also shows that the total effects of exchanging production processes to produce the same polymer (PE) are limited. Furthermore, differences between PE and PP production appear to be very small. Finally it is shown that the influences of reducing plastic waste from plastic processing, packing and assembling on total lifecycle fossil fuels and feedstocks use, CO_2 emissions and costs are small. Note that substitution is analysed on a mass basis only. Substitution may allow different product designs, changing the specific material use beyond the sensitivities as shown in Figure 3.

Plastic waste management

In the base case 781 ktonnes of post consumer plastic wastes are produced, as well as 123 ktonnes of production and processing wastes (see Chapter 3). Because of large differences in material quality and processability between these two plastic waste types, actual mixes of processes for plastic waste management differ considerably. In the base case the process mix for post consumer waste management consists of 55% landfilling, 28% incineration with heat recovery, 6% incineration without heat recovery and 11% mechanical recycling (APME, 1994). For production and processing waste management these percentages amount to 25%, 15%, 4% and 56% respectively (CBS, 1992). This shows that in the base case already a relatively large part of production and processing waste is reused. The remaining improvement potentials for production and processing plastic waste are relatively small, compared to improvement potentials for post consumer plastic waste. Therefore we only investigate alternative process mixes for post consumer plastic waste management.

Figure 4 shows the sensitivities of the plastics lifecycle for changing the shares of processes for post consumer plastic waste management[19] while keeping constant the shares of processes for production and processing plastic waste management.

From Figure 4 it can be seen that increasing the share of each process reduces total fossil fuels and feedstocks use, except for landfilling (which makes no use of the material or energy content of the plastic waste). The largest reductions of total fossil fuels and feedstocks use are shown to be achieved by blast furnace injection and mechanical recycling. All processes except incineration and gasification reduce CO_2 emissions. CO_2 emissions are most largely decreased by landfilling, mechanical recycling and selective dissolution. The effect on total costs varies considerably between the investigated processes. Substantial cost reductions are only achievable by increasing the share of mechanical recycling (we will discuss this in the next section). Increasing shares of all other processes leads to higher costs. Especially gasification, hydrogenation and pyrolysis appear to be very expensive.

[19] While increasing the share of one process, shares of the (other) processes used in the base case (landfilling, incineration) are decreased proportionally, except for mechanical recycling, which remains constant at 11%.

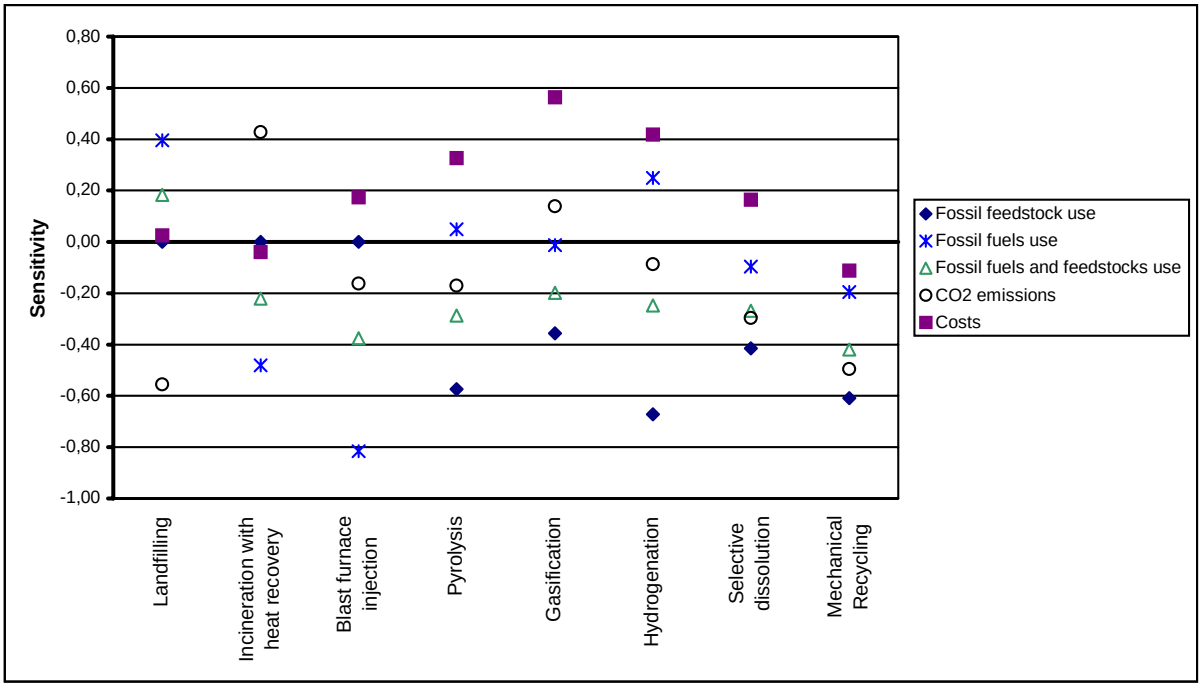

Figure 4 Sensitivities of total fossil fuels and feedstocks use, CO_2 emissions and costs of the whole plastics lifecycle for increases of the shares of specific processes for plastic waste management relative to the base case.

5.5 Discussion

5.5.1 Interpretation of the results

The results of our study should be interpreted in relation to the system boundaries that were applied. The calculations concern the lifecycles of the so-called “bulk-plastics” PE, PP, PVC and PS in The Netherlands in 1990, which encompassed 69% of plastic consumption. The calculations include all processes for the production of these bulk-plastics and their feedstocks, as well as all waste management processes. Energy use and CO_2 emissions of transports were not accounted for, neither are possible energy use and CO_2 emissions during final consumption.

5.5.2 Discussion of the results

Figure 2, Figure 3 and Figure 4 show the sensitivities of the total plastics lifecycle for increasing the shares of specific processes, starting from the base case. Reduction potentials for fossil fuels and feedstocks consumption and CO_2 emissions are determined by a combination of sensitivities of the lifecycle for changes in process mixes and the application potentials of those changes. Application potentials are limited by the demands on material properties that are made by products and processes in the lifecycle.

Alkenes production

In 1990 the following alkenes mix was produced in Western Europe: ethylene: 41%, propylene: 20%, C_4 fraction: 13% and BTX fraction: 27%. This product mix is a result of the process mix used for alkenes production and the respective outputs of the alkenes production processes. If the mix of alkenes production processes is changed, the total alkenes mix will change too. This means that the chemical industry, by which the alkenes are processed, must adapt to this change. It is questionable whether the chemical industry is able to fabricate its products from a changed alkenes mix. Probably it can adapt to minor variations, but large changes may cause difficulties on the short term. However, further adaptations can be made in the plastics processing industry, because specific plastic products can be made from different plastics.

Ethylene and propylene are the most important alkenes in the plastics lifecycle. Therefore the alkenes mix produced is most accurately characterised by the ratio propylene / ethylene (p/e ratio). In the base case this ratio has a value 0.49. The p/e ratio is a function of the mix of alkenes production processes. The p/e ratio may be varied between certain limits. If, for example, a large part of alkenes would be produced by biomass flash pyrolysis, a process that hardly delivers any propylene, the p/e ratio would approximate zero and the plastics lifecycle would lack propylene to produce PP. This problem could partly be solved by using propylene from other sources (for example from refineries) and partly by substitution of propylene by ethylene. The flexibility of the plastics lifecycle to adapt to changes in the propylene / ethylene ratio is relatively large, because most material properties of ethylene and propylene are comparable. We estimate that a variation of between -50% and +50% could be handled without major problems.

The sensitivities from Figure 2 show that exchanges between the four conventional alkenes production processes (steamcracking of ethane, LPG, naphtha and gas oil) only marginally affect fossil fuels and feedstocks use and CO_2 emissions. So changes between these four conventional processes will not lead to large reductions. Of the four other, alternative processes, the MTO process combined with methanol production from natural gas neither appears to be a useful option, because it combines higher fossil fuels and feedstocks use and higher CO_2 emissions with higher costs. Oxidative coupling of natural gas is expected to perform better. Because it produces little propylene its application potential is limited: if 55% of alkenes production were replaced by oxidative coupling (Case A1, see Table 15), the p/e ratio would drop by 50%, total fossil fuels and feedstocks use would be reduced by 5%, CO_2 emissions by 10%. Total lifecycle costs, however, would raise by 8%.

Figure 2 shows that processes based on biomass feedstocks have much larger impacts on fossil fuels and feedstocks consumption and CO_2 emissions. The MTO process combined with methanol production from biomass produces relatively much propylene (p/e ratio =

1.11), the flash pyrolysis process produces no propylene at all (p/e ratio = 0). This means that a combination of these processes can lead to a p/e ratio comparable to the actual 1990 p/e ratio. Thus, if the actual alkenes production processes mix is replaced by a combination of biomass flash pyrolysis and MTO from bio-methanol, no further adaptations in the lifecycle are needed. This, together with the high sensitivities of total fossil fuels and feedstocks use and CO_2 emissions, makes this combination a very promising option to reduce fossil fuels and feedstocks consumption of and CO_2 emissions from the plastics lifecycle. If these processes would each replace 25% of alkenes production (Case A2), the p/e ratio would only marginally change, total fossil fuels and feedstocks use would be reduced by 29%, CO_2 emissions by 19%. Costs would increase by 11%. Complete replacement of alkenes production by these two biomass processes (50% / 50%, Case A3) would approximately double these percentages.

Although biomass based processes technically appear to be promising options for fossil fuels and feedstocks consumption and CO_2 emission reduction, they lead to substantially higher total costs. This is also observed by Patel *et al.* (1999). They compared CO_2 emission reductions from a replacement of conventional processes for alkenes production by biomass based processes to CO_2 emission reductions from replacement of conventional electricity production by electricity production by biomass gasification. They found that using biomass for electricity production leads to higher CO_2 emission reductions and lower cost increases than using biomass for alkenes production. Electricity production is no part of our study. Nevertheless, large-scale use of biomass for electricity production (or for fuels for the transportation sector) would limit or block alkenes production from biomass. In that case the only promising reduction option in alkenes production would be oxidative coupling with, as described above, limited application potential, modest sensibilities and, hence, limited reduction potentials.

Polymers production

Changing the mix of processes for polymers production also means changing the mix of polymers that are produced and hence changing the mix of polymers that are used to produce plastic products. Part of the plastic products can, in principle, be produced from different plastic types. Other plastic products make more specific demands on the material they are produced of. For these products it is more difficult to find alternative plastics types. This shows that, for the whole plastics lifecycle, there is a certain flexibility in the shares of plastic types used. This flexibility, however, is limited. The boundaries are not easily estimated, because of the vast amount of different plastic products, each making specific demands on material properties.

The results of the calculations (Figure 3) show that, with respect to CO_2 emission reduction, both PE and PP are more favourable than PS and PVC. PS performs most badly, on CO_2

emission reduction as well as on reduction of fossil fuels and feedstocks consumption. This can be an incentive to use as little PS as possible. However, because the use of PS also causes the highest costs, it is reasonable to assume that in practice PS is only used for products for which PS has favourable properties. This means that the substitution potential of PS by other polymers is limited. Figure 3 also shows that, with respect to reduction of fossil fuels and feedstocks consumption, PVC performs substantially better than any of the other plastic types (this is caused by the fact that part of the fossil feedstocks is substituted by chlorine). However, the use of more PVC leads to higher CO_2 emissions. Furthermore, PVC has a number of other drawbacks from an environmental point of view, like the danger of dioxins emissions in waste incineration and the high toxicity of the chlorine that is used to produce VCM. During the last decades there has been an ongoing discussion on the environmental aspects of PVC between environmental organisations and the chemical industry. This has lead to increased caution with respect to the use of PVC, trying to avoid it if possible, at least for products with a short lifetime.

The calculations show that individual changes on a limited scale (like increasing the share of gas phase PE polymerisation), although increasing the energy efficiency of specific processes, have little effect on the total energy consumption and the total CO_2 emissions of the whole lifecycle, but may be important for the specific phase in the life-cycle. The same can be concluded about the reduction of plastic waste from plastics production and processing. Because plastic production and processing waste streams are small compared to total plastics consumption, measures to reduce them only marginally affect total fossil fuels and feedstocks consumption and CO_2 emissions of the total lifecycle.

Plastic waste management

Application potentials of plastic waste management technologies are limited by the quality of the plastic waste in relation with the quality of the product(s) to be obtained. Of the eight plastic waste management technologies investigated in this study, only landfilling and incineration (with or without heat recovery) can be applied directly to plastic waste in municipal solid waste. In order to enable application of the other processes, plastic waste must either be separated from municipal solid waste, or collected separately. Therefore we modelled a separation process ‘upgrading to mixed plastic waste’. Using this upgrading process application potentials of all plastic waste management processes are unlimited, except for mechanical recycling. Mechanical recycling needs unmixed plastic waste, existing of only one clearly defined plastic type, in order to produce regranulate of sufficient quality. Currently, only a limited part of post-consumer waste consists of clearly defined, unmixed plastic wastes, like rejected multiple-use bottles or discarded window frames. In practise most post consumer plastic waste ends up in municipal solid waste and is, therefore, not suitable for mechanical recycling, even after ‘upgrading to mixed plastic waste’. This means that the

application potential for mechanical recycling is limited, unless high precision separation technologies, blending techniques using compatibilisers, or highly developed waste collection systems (in which the different plastic types are collected separately) are developed.

The results (Figure 4) show that the two conventional technologies for plastic waste management (landfilling and incineration) are problematic with respect to the environmental aspects investigated in this study. Landfilling involves no CO_2 emissions, but makes no use of the energy content of the plastic waste. So increasing the share of landfilling also means increasing the net amount of fossil fuels and feedstocks needed in the plastics lifecycle. Incineration (with heat recovery) means decreased net fuels use, however combined with increased CO_2 emissions[20]. For the same reason gasification of plastic waste for hydrogen production appears to be problematic. Although it reduces net fossil fuels and feedstocks consumption, it leads to increased CO_2 emissions (although less pronounced than incineration) and to substantially increased costs. Therefore, gasification appears to be no interesting option for simultaneously reducing fossil fuels and feedstocks use and CO_2 emissions. Hydrogenation is shown to perform slightly better, but its costs appear to be high.

The four remaining technologies (blast furnace injection, pyrolysis, selective dissolution and mechanical recycling) each reduce both fossil fuels and feedstocks use and CO_2 emissions, with modest cost increase or even a slight decrease (mechanical recycling). Costs for mechanical recycling are based on the processing of easily collectable unmixed plastic waste streams. When increasing the share of mechanical recycling, less easily collectable waste streams will be processed, leading to higher costs. We estimate that 25% mechanical recycling of post consumer plastic waste (Case W1) is the maximum achievable without substantial cost increase. Therefore, extensive reductions of fossil fuels and feedstocks consumption and CO_2 emissions can only be obtained by a combination of two or more processes. For example, replacing the 1990 plastic waste management process mix for post consumer waste by a combination of 25% mechanical recycling, 25% selective dissolution and 50% blast furnace injection (Case W2) would lead to a CO_2 emission reduction of 23%, a reduction of fossil fuels and feedstocks use of 32% and a cost increase of 11%.

5.5.3 Scenarios

In paragraph 5.5.2 it was shown that especially amongst the measures intervening in the production of alkenes and in the management of plastic waste there are promising options to simultaneously reduce total fossil fuels and feedstocks use and CO_2 emissions of the whole plastics lifecycle. Measures intervening in alkenes production and plastic waste management

[20] This is due to the relatively low energy efficiency of waste incineration (20-22%, Gielen, 1994) compared to conventional electricity production (42%, Eggels *et al.*, 1997).

can be combined in order to get even higher reductions. To get an indication of the reduction potentials achievable we have calculated the combined effects of several measures, as shown in Table 15.

Table 15 Effects on CO_2 emissions, total fossil fuels and feedstocks use, costs and p/e ratio of measures intervening in alkenes production, plastic waste management and combinations of both.

Cases:	**A1**	**A2**	**A3**	**W1**	**W2**	**A1 / W1**	**A1 / W2**	**A2 / W1**	**A2 / W2**	**A3 / W1**	**A3 / W2**
Alkenes production:											
Oxidative Coupling	55%					55%	55%				
Flash pyrolysis		25%	50%					25%	25%	50%	50%
MTO (bio-methanol)		25%	50%					25%	25%	50%	50%
Plastic waste management:											
Mechanical recycling				25%	25%	25%	25%	25%	25%	25%	25%
Selective dissolution					25%		25%		25%		25%
Blast furnace injection					50%		50%		50%		50%
Changes [%]:											
CO_2 emissions	-10	-19	-40	-7	-23	-17	-31	-23	-28	-42	-33
Total fossil fuels and feedstocks use	-5	-29	-62	-6	-31	-11	-36	-32	-55	-62	-82
Costs	+8	+11	+24	-2	+11	+6	+18	+9	+20	+20	+30
p/e ratio	-50	+7	+13	+0	+0	-50	-50	+7	+7	+13	+13

From Table 15 it can be seen that high reductions of fossil fuels and feedstocks consumption and CO_2 emissions can be achieved using combinations of measures. However, combinations of measures involve added costs. On closer examination, Table 15 also shows that the effects of a combination of measures are not equal to the sum of the effects of the individual measures. This suggests that measures are not independent. Measures may even counteract each other, which is the case for CO_2 emission reduction by a combination of cases A3 and W2.

5.5.4 Sensitivity for data deficiencies

The calculations are based on a large amount of data. Although we have tried to use data that are reliable, up-to-date and representative, inaccuracies are unavoidable. In this paragraph we discuss possible data inaccuracies and their influence on the results.

The data that are used can be divided into two groups.

The first group consists of data that are needed to construct the material balance:

(a) data on the final consumption of plastic products and the production of plastic waste
(b) data on process mixes used to produce plastic products and their feedstocks, as well as on process mixes used for plastic waste management
(c) data on product yields of the processes used in the plastics lifecycle

The second group consists of data that are needed to calculate total energy use, total CO_2 emissions and total costs. It encompasses:

(d) process data on energy use, CO_2 emissions and costs
(e) energy prices

Data on final plastics consumption (a) were calculated using the STREAMS method. A detailed discussion on the accuracy of these data can be found in Chapter 3. Because we included a number of improvements to the STREAMS method (see paragraph 5.2.2) and because we used aggregated results, data inaccuracies are expected to be quite small.

Data on process mixes (b) are used to construct a material balance for the base case. Subsequently, these process mixes are varied, in order to calculate the sensitivities of total fossil fuels and feedstocks use, total CO_2 emissions and total costs for these variations. This means that inaccuracies in data on process mixes mainly affect total fossil fuels and feedstocks use, CO_2 emissions and costs *in the base case*. Because all changes in fossil fuels and feedstocks use, CO_2 emissions and costs are calculated relative to these base case values, sensitivities for all processes are affected. However, because all sensitivities are calculated relative to the same base case, they are all affected in the same way, so that conclusions drawn from the calculated sensitivities remain unchanged.

Data on product yields of the processes used in the plastics lifecycle (c) largely influence the material balance, because they determine for each process the relation between the processing of input materials and the production of output materials. So potentially high inaccuracies in the results of the calculations may be expected from inaccuracies in data on product yields. However, research and development of new processes pays much attention to product yields. Therefore, literature data on product yields are very reliable. This means that, although inaccuracies in data on product yields of processes can theoretically cause large deviations in the results of the calculations, in practise no major inaccuracies are to be expected.

Inaccuracies in data on energy use, CO_2 emissions and costs of specific processes (d) only marginally influence the results of the calculations, because the contribution of specific processes to total lifecycle energy use, CO_2 emissions and costs is limited. Evidence for this statement can be found in Figure 3. Sensitivities of total fossil fuels and feedstocks use, CO_2

emissions and costs for exchanging liquid phase, solution and suspension processes for PE production by the gas phase process (mainly differing in energy consumption) are shown to be very small. This shows that exchanging specific processes that only differ in energy use, CO_2 emissions or costs only marginally influences total energy use, CO_2 emissions and costs.

Figure 5 shows that energy prices (e) have fluctuated considerably during the last decade. In order to investigate the influence of energy prices on the results of our calculations we ran the model twice, once using the 1991 energy prices (high oil price / low gas and electricity prices) and once using the 1998 energy prices (lower oil price / higher gas and electricity prices)[21]. The results of both model runs (Table 16) show that energy prices first of all influence sensitivities of total lifecycle costs for *alkenes production*. Compared to 1991 energy prices, 1998 energy prices bring about changes in sensitivities of total costs in alkenes production from –0.01 to +0.12. Especially those alkenes production processes that use natural gas as feedstock get relatively more expensive with higher gas prices and lower oil prices. Table 16 shows that the influences of changing energy prices on sensitivities of total costs in polymers production and waste management are more limited (changes in sensitivities between –0.02 and +0.05). Comparing the sensitivities of total costs from Table 16 with those in Figure 2 to Figure 4, it is clear that changes in energy prices with up to about 30% only marginally influence the conclusions. This can be explained by the fact that energy costs make up a limited share of total costs (10.5%).

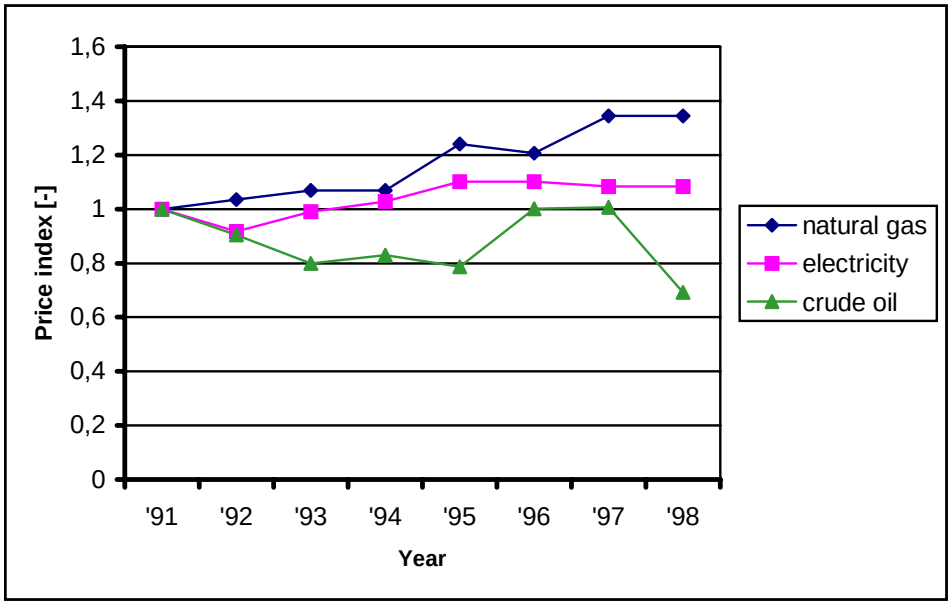

Figure 5 Energy price indexes for the Netherlands in the years 1991-1998 (CBS, 1998), (Eurostat, 1992-1998)

[21] Note that these are extremes; the results from paragraph 5.4 are based on mean energy prices for the period 1991-1998 (see paragraph 5.2.5)

Table 16 Sensitivities of total lifecycle costs [-]. Results of the calculations using 1991 and 1998 energy prices

	1991 energy prices	1998 energy prices	Change 1998-1991
Alkenes production:			
Ethane steamcracking	0.03	0.12	0.09
LPG steamcracking	0.00	0.00	0.00
Naphtha steamcracking	-0.01	-0.02	-0.01
Gas oil steamcracking	0.00	0.00	-0.01
Oxidative coupling	0.15	0.25	0.10
MTO, methanol from natural gas	0.14	0.26	0.12
MTO, methanol from biomass	0.23	0.29	0.06
Biomass flash pyrolysis	0.17	0.23	0.06
Polymers production:			
PE	-0.07	-0.09	-0.01
PP	-0.02	-0.02	-0.01
PS	0.17	0.16	-0.02
PVC	-0.03	0.00	0.03
PE gas phase	-0.03	-0.03	0.00
PP instead of PE	0.02	0.02	0.00
Processing waste	0.03	0.03	0.00
Waste management:			
Landfilling	0.02	0.03	0.01
Incineration with heat recovery	-0.03	-0.04	-0.01
Blast furnace injection	0.16	0.20	0.04
Pyrolysis	0.31	0.35	0.05
Gasification	0.56	0.57	0.01
Hydrogenation	0.40	0.45	0.05
Selective dissolution	0.15	0.18	0.03
Mechanical Recycling	-0.13	-0.09	0.03

In summary, the considerations of this paragraph show that the results of our calculations are fairly robust. Another consideration gives an indication of the congruency of the model and the real world. From Figure 2, Figure 3, Figure 4 and Table 15, it can be seen that changing process mixes almost always leads to higher costs than actual (base case) process mixes. This is an indication that the model fairly represents reality, because up till now process mixes have been chosen mainly based on lowest costs. Our calculations confirm that actual process mixes are cost effective under current economic conditions.

5.6 Conclusions

We have calculated that the final consumption of plastics products in The Netherlands in 1990 produced 2844 ktonne of CO_2 emissions from the total plastics lifecycle. In total 74.7 PJ of fossil fuels and feedstocks were needed in the plastics lifecycle, 39.8 PJ of which were used

as feedstock and 34.9 PJ as fuel. There are a lot of possible measures to reduce fossil fuels and feedstocks consumption and CO_2 emissions in the lifecycle of plastics. Because energy consumption and CO_2 emissions are distributed rather evenly over all stages of the lifecycle, large reductions in total energy consumption and CO_2 emissions can only be achieved by a large number of simultaneous measures or by measures that influence large parts of the lifecycle. In this study we have investigated the influences of the latter, structural changes in the plastics lifecycle on total lifecycle fossil fuels and feedstocks consumption, CO_2 emissions and costs.

With respect to alkenes production we have found that changes in steamcracker feedstocks only marginally influence total fossil fuels and feedstocks consumption and CO_2 emissions. A number of processes that are currently under development appear to be more promising, *e.g.* oxidative coupling of natural gas. The highest reductions in total fossil fuels and feedstocks use and CO_2 emissions are achieved by using new processes that use biomass as feedstock: biomass flash pyrolysis and the methanol-to-olefins process combined with methanol production from biomass. Especially a combination of the latter two routes turns out to be capable of inducing large reductions.

Although changes of the polymers mix theoretically induce large changes in the plastics lifecycle, in reality no large reductions in total fossil fuels and feedstocks consumption and CO_2 emissions are to be expected, because substitution potentials between different plastic types are limited and differences in energy use and CO_2 emissions for producing different plastic types are relatively small.

Of the investigated plastic waste management processes, we have shown that landfilling and incineration do not allow simultaneous reductions in fossil fuels and feedstocks consumption and CO_2 emissions. Due to a relatively large share of waste incineration in the base case (33%), plastic waste management has a relatively large share in the total CO_2 emissions arising from the plastics lifecycle. A policy aiming both at CO_2 emission reduction and at increased waste incineration is shown to be rather ambivalent, because waste incineration enhances total CO_2 emissions, even if the energy content is used to produce electricity. The investigated gasification process (with hydrogen production) also leads to increased CO_2 emissions. The process can, however, be modified to produce methanol instead of hydrogen. Combined with the methanol-to-olefins process this modified process probably performs better. Further investigation should aim at studying the influences of this modified gasification process on fossil fuels and feedstocks consumption, CO_2 emissions and costs. All other investigated plastic waste management processes (blast furnace injection, pyrolysis, hydrogenation, selective dissolution and mechanical recycling) reduce both fossil fuels and feedstocks consumption and CO_2 emissions and are, therefore, interesting options from an environmental point of view. Highest reductions are achieved by mechanical recycling,

followed by selective dissolution and blast furnace injection. Effort should be made to clear away the obstacles that limit the share of mechanical recycling, by developing appropriate blending and separation techniques.

Virtually all improvement options lead to higher costs. The results of our calculations show that, by using a combination of biomass pyrolysis, the methanol-to-olefins process (with methanol from biomass), mechanical recycling, selective dissolution and blast furnace injection, CO_2 emission reductions of about 30% and fossil fuels and feedstocks reductions of up to 60% are achievable, resulting, however, in a cost increase of about 20%.

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Chapter 6

Summary and conclusions

This thesis deals with the industrial metabolism of plastics. The term ‘Industrial Metabolism’ refers to the physical economic system of production and consumption, in which materials flow via complicated patterns. The aim of this thesis is to analyse the flows of plastics in the industrial society, as well as the energy requirements and CO_2 emissions involved. This must lead to a better understanding of the possibilities to reduce the consumption of materials and energy, as well as the CO_2 emissions that are associated with the consumption of plastic products.

The main research question of this thesis is:

Which are promising options for decreasing material consumption, energy consumption and CO_2 emissions in the lifecycle of plastics?

The research described in this thesis mainly focuses on the situation in The Netherlands and Western Europe.

Since the 1970’s consciousness has grown that human activity influences the environment in unintended ways. At first major concern was on the finiteness of natural resources, especially fossil energy sources. Even though in the short term no shortage is to be expected, it is clear that current energy consumption patterns are far from being sustainable. Nevertheless, concern about the exhaustion of natural resources has declined. But at the same time other environmental issues connected to the use of fossil fuels have come to the foreground. It is believed that especially emissions from fossil fuel combustion have a large impact on the environment and on human health, via small particle emission, smog forming, acidification and climate change.

Currently, one of the main environmental problems is seen to be global climate change, caused by an increase in the greenhouse effect. As described by the UN Intergovernmental Panel on Climate Change (IPCC) the concentration of greenhouse gasses (GHGs) in the atmosphere has increased considerably during the past century, which has lead to an increase of the greenhouse effect. This has most probably resulted in the observed increase of the global average surface temperature of about 0.6°C. Especially the increase of the atmospheric concentration of carbon dioxide (CO_2) plays a major role in the enhanced greenhouse effect.

The CO_2 concentration of the atmosphere has grown rapidly, partly caused by fossil fuels combustion and partly because of land-use changes, especially deforestation.

In order to combat these problems, measures are sought, aiming to reduce the consumption fossil fuels and emissions of greenhouse gasses. Many measures have already been implemented, while new technology developments provide new opportunities today and in the future. However, because of the growth in population and the increased levels of economic activity, both fossil fuels consumption and the emission of greenhouse gasses are still growing. This means that more measures are needed to improve the productivity of fossil fuels use and to reduce GHG emissions.

Recently, consciousness has risen that considerable reductions in fossil fuels consumption and in emissions of greenhouse gasses can be achieved by improved material management. If less materials are used, less materials have to be produced and less feedstocks have to be extracted from the earth, requiring less energy, causing lower emissions and generating less waste. For plastics, the materials that are investigated in this thesis, the link between material use on the one hand and fossil fuels consumption and CO_2 emissions on the other hand is very tight, because plastics are produced from fossil feedstocks.

There are many possible measures to the materials system that can contribute to a reduction of fossil fuels consumption and CO_2 emissions. These measures include recycling, waste prevention, downgauging, product life prolongation and substitution. Because the implementation of those measures may not be easy, a thorough analysis of the effects and consequences of different measures is needed to enable society to evaluate the measures and make sound policy choices. Especially for the most promising measures, which have a wide impact on the materials system (like material recycling and substitution), a detailed analysis is needed to facilitate an estimate of the overall impacts on fossil fuels consumption and CO_2 emissions.

Understanding of the materials system is one of the major goals of a research discipline called ‘Industrial Ecology’. Industrial Ecology builds on the concept of Industrial Metabolism. This concept argues the analogy between biological organisms and the economic system, both of which are materials-processing systems driven by a flow of energy. However, there is one major difference between natural metabolism and industrial metabolism, in that the industrial system does not generally recycle its nutrients. The analogy between natural metabolism and industrial metabolism is intended to be a guideline for seeking options to achieve a sustainable industrial economy.

The study of the industrial metabolism of materials is called Material Flow Analysis (MFA). Material Flow Analysis can help to identify and analyse opportunities for increasing resource

productivity. When combined with emission analysis, Material Flow Analysis can help to identify those areas that need attention for pollution prevention.

The approach followed in this thesis can be summarised as follows:

- First a material flow analysis of plastics through society is conducted, resulting in a material balance of the plastics lifecycle.
- Secondly, energy and emissions analyses are conducted on all industrial processes that are used in the lifecycle of plastics to produce or process plastics and their feedstocks, as well as on processes for plastic waste processing.
- The results of the material flow, energy and emission analyses are combined to get an overview of material use, energy consumption and CO_2 emissions that are related to the lifecycle of plastics.
- Subsequently, improvement options are defined that aim to change or reduce material consumption, leading to a reduction of energy consumption and CO_2 emissions.
- The effect of these improvement options is investigated by calculating their impact on material consumption, energy consumption and CO_2 emissions.

From this analysis conclusions can be drawn on the usefulness of the improvement options, while different options can be evaluated and compared in order to find the most effective measures.

In Chapter 2 a new method for material flow analysis is proposed to calculate physical material flows through society. For the development of material, product and waste oriented policies, knowledge about the flow, use and disposal of materials in society is a prerequisite. The risks of taking policy measures leading to sub-optimum solutions of environmental problems call for an integral survey of material flows through society.

Until now integral analyses of physical material flows have been lacking. Because of problems like differences in definitions, in subdivisions of flows and in reference years, it is difficult to relate data from different sources to get an overall view. Furthermore, data on the *final consumption* of materials is generally unavailable. Often *apparent consumption* data is used, calculated as the production of materials plus the imports of materials minus material the exports of materials. However, because complex products consist of various materials and as packaging materials and products are imported or exported together, part of the materials are invisible in statistics. Therefore, apparent consumption is not a good estimate for final consumption in an economy.

In Chapter 2 a method is developed, called STREAMS (STatistical REsearch for Analysing Material Streams), to analyse the input, flow and final consumption of materials through society. The STREAMS method is based on the so-called supply and use tables, which

describe a country's economy in terms of the supply and use of materials, products and services by industries, service sectors and consumers. From the supply and use tables information can be drawn on the supply and use of materials and products by individual industries. By estimating the purpose of the use of materials (*e.g.* packaging material, product part, or final product), it is possible to allocate these materials to the products that are manufactured by that industry. This way, the materials are tracked on their way from extraction of raw materials to the final consumption of products and beyond, into the stage of wastes.

The STREAMS method has the advantage of deriving almost all data from one source. The method is unique in providing detailed information on the final consumption of products, a stage that is largely neglected in literature, but which is the most accurate measure for a country's materials consumption.

In Chapter 3 the STREAMS method is examined in an assessment of the flows of plastics in The Netherlands in the reference year 1990. We calculated the total final consumption of plastics in the Netherlands at 1260 ktonnes. This figure is considerably higher than the apparent consumption of about 1140 ktonnes that is calculated rather roughly from the production, imports and exports of primary plastics. Therefore we conclude that apparent consumption, although easily calculable, is a rather poor approximation for final consumption.

The case study on the final consumption of plastics in The Netherlands shows that, by using the STREAMS method, detailed information can be obtained on materials flows in all stages of their lifecycle. However, the STREAMS method faces a number of problems that should be solved in order to get more accurate results on disaggregated lebels. We estimate the mean deviation of the results of our analysis on the lowest aggregation level at ± 30%. Results presented on higher aggregation levels are much more accurate. Part of the deviation is caused by factors that are typical for the situation in The Netherlands, a small open economy with a limited number of producers for most products, like a high amount of confidential supplies. Other factors are inherent to the method, for example the fact that it starts from financial statistical data, which have to be converted into physical amounts using mean prices. A number of factors can be eliminated by refinement of the method. Notably, the conversion from monetary into physical units and the allocation step can be improved considerably, leading to more accurate results. We expect that these refinements diminish the mean deviation of the results on the lowest aggregation level to about ± 15%.

Chapter 4 investigates the amount of fossil fuels that is used - as energy source and as feedstock - and the amount of carbon dioxide (CO_2) that is emitted in the Western European lifecycle of plastics. The amount of fossil fuels used *as feedstock* is calculated from a material

balance of the Western European plastics lifecycle. The amount of fossil fuels used *as energy source* and the CO_2 emissions that are involved are deduced from an investigation on the energy consumption and CO_2 emissions of all major processes that constitute the lifecycle of plastics. These include processes such as crudes extraction and processing, alkenes production, intermediates production, polymers production, plastics processing, auxiliary materials production and plastic waste management

From our calculations we conclude that in 1994 the Western European lifecycle of plastics used in total approximately 2300 PJ of energy carriers, which is 4.4% of the total Western European energy consumption in that year. Approximately 1100 PJ of these were used as feedstock, the rest as energy source. CO_2 emissions from the lifecycle of plastics amounted to approximately 80 Mtonnes, 2.3% of the total Western European CO_2 emissions in 1994. The largest contributions to the total consumption of fossil fuels by the plastics lifecycle came from *polymers production* (28%), *alkenes production* (23%) and *plastics processing* (18%). These stages also produced the largest shares of CO_2 emissions in the total CO_2 emissions of the Western European lifecycle of plastics: 27%, 17% and 14% respectively.

In Chapter 5 technological measures leading to structural changes in the lifecycle of plastics are investigated to reduce both CO_2 emissions and fossil fuels and feedstocks consumption. For measures that affect large parts of the plastics lifecycle, *e.g.* alternative feedstocks for alkenes production (changing production routes), alternative plastic types (material substitution) or alternative processes for plastic waste management (increasing materials recycling), it may not be easy to estimate the overall effects on materials and energy use, CO_2 emissions and costs. An overview of these effects can only be obtained if a calculation model is used that takes into account all interrelations. In Chapter 5 we discuss and apply a method to calculate the influences of structural changes on the consumption of fossil feedstocks and fuels, CO_2 emissions and costs of the total lifecycle. A range of measures is investigated, from the use of alternative feedstocks for alkenes production (including biomass based feedstocks), to substitution between plastic types and enhanced plastic waste recycling.

From Chapter 5 the following conclusions are drawn:

- Changes in steamcracker feedstocks only marginally influence total fossil fuels and feedstocks consumption and CO_2 emissions. Higher reductions can be achieved by using new processing routes that use biomass as feedstock: biomass flash pyrolysis and the methanol-to-olefins process combined with methanol production from biomass. Especially a combination of these two routes turns out to be capable of inducing large reductions.

- Because substitution potentials between different plastic types are limited and differences in energy use and CO_2 emissions for producing different plastic types are relatively small, no large reductions are to be achieved by substitution between plastics types (unless this would enable product changes increasing material efficiency).

- Landfilling and incineration of plastic waste do not allow simultaneous reductions in fossil fuels and feedstocks consumption on the one hand and CO_2 emissions on the other hand. Although it is a cheap and relatively easy applicable option, increasing the share of waste incineration is no valuable option, because it would increase overall CO_2 emissions.

- Largest reductions of CO_2 emissions, fossil fuels consumption and feedstocks consumption by measures aiming at enhanced waste management are achieved by increasing the contribution of mechanical recycling, selective dissolution or blast furnace injection. Effort should be made to clear away the obstacles that limit the share of mechanical recycling, by developing appropriate blending and separation techniques.

- We estimate that structural changes in the lifecycle of plastics in The Netherlands can lead to a reduction in the consumption of fossil fuels of up to 60% and a CO_2 emission reduction of up to 30%. These reductions can for example be achieved by large scale use of biomass as feedstock for the production of plastics, possibly combined with an increased share of plastic waste recycling. Realisation of these options may be accompanied by a cost increase of the total plastics lifecycle of about 20%.

Final remarks

Based on the research presented in this thesis we can draw several important conclusions for the field of material flow analysis and the impact that material use has on climate change, as well as for the assessment of emission reduction opportunities.

A better understanding of material flows in an economy is essential to develop effective strategies for sustainable management of product chains (or life-cycles). Without this information policies may be implemented which might not result in the expected results or which could have unforeseen (economic) impacts. For example, the optimum environmental and economic management of waste streams in an economy depends on good estimates of materials consumption and the different waste streams and their compositions. For an open economy like the Netherlands we found that apparent consumption is an inadequate measure for final materials consumption. In a world where regional and national economies will increasingly open to international trade, the call for adequate measures of materials consumption is becoming even more important.

In this thesis we have developed a method to accurately estimate the material flows through an economy and tested this method with statistical data for plastics consumption in The Netherlands. This analysis showed that the actual final plastic consumption in The Netherlands is higher than the apparent consumption based on available statistics. This has consequences for waste management policy as well as for CO_2 emission reduction strategies. For example, the future amounts of plastics entering the waste management system will likely be higher than previously thought, leading to higher future CO_2 emissions, given the current emphasis on waste incineration in the Netherlands.

Full information on the material flows allows an integrated assessment of options to reduce GHG emissions and / or to improve energy efficiency. The material flow information allows us to compare different measures at different stages in the life-cycle of a material or product, up and down the product-chain. For example, in this thesis we compared measures to replace feedstocks with measures in product manufacturing and waste management to estimate the impact on GHG emissions and fossil fuels consumption over the whole lifecycle.

Based on the analysis we have found several areas for future research, including:

- The need to improve the reliability of the proposed STREAMS method at low aggregation levels. Initial improvements have been developed and tested. Further improvement depends heavily on the data quality of the statistical information underlying the STREAMS method. Hence, we strongly recommend improved statistical data collection at disaggregated levels of product categories.

- Using the STREAMS method we have provided a ‘snap-shot’ of plastics flows in The Netherlands in the year 1990. Dynamic methods using historic data for other years may help to develop an improved method for forecasting future material flows. For example, historic datasets will help to get a better view of the accumulation of plastics in an economy and of their lifetime in the economy. Historic datasets will help to make better estimates of future plastic waste volumes and sources. Because of the labour intensity of such analyses we recommend to focus on key material streams from the perspective of waste and / or GHG management.

- Dynamic material flow analyses will also help to improve knowledge on consumption patterns and product mixes within the economy. As such dynamic material flow analyses could be integrated in energy and GHG emission forecasting models to improve forecasts of energy use and GHG emissions. It will also help to compare the different options in the energy and materials-system. The work on the MATTER-model, for which the results of this thesis were used, is an example of a first step into this important new direction.

- Finally, the integration of material flow analysis in policy design and development needs to be strengthened, especially in waste and GHG-emission management. While models can help with this, further study of the socio-political aspects of material use and the ways to direct these into environmentally and economically sustainable development patterns is needed.

Samenvatting en Conclusies

Dit proefschrift gaat over het industrieel metabolisme van kunststoffen. De term ‘Industrieel Metabolisme’ heeft betrekking op het fysieke economische systeem van productie en consumptie, waarin materialen ‘stromen’ volgens gecompliceerde patronen. Het doel van dit proefschrift is een analyse van kunststofstromen in de industriële samenleving, alsmede van het energiegebruik en de CO_2-emissies die daarmee gepaard gaan. Dit moet leiden tot een beter zicht op de mogelijkheden om het energie- en materiaalgebruik, dat het gevolg is van het gebruik van kunststoffen, te reduceren en de bijbehorende CO_2-emissies te verlagen.

De centrale onderzoeksvraag van dit proefschrift luidt als volgt:

Wat zijn veelbelovende opties om het materiaalgebruik, het energiegebruik en de CO_2-emissies in de levenscyclus van kunststoffen te verminderen?

Het onderzoek in dit proefschrift richt zich hierbij voornamelijk op de situatie in Nederland en West Europa.

Sinds de zeventiger jaren van de vorige eeuw is het bewustzijn gegroeid dat het menselijk handelen het milieu beïnvloedt. Aanvankelijk maakte men zich vooral zorgen over de eindigheid van natuurlijke bronnen en met name over de eindigheid van fossiele brandstoffen. Hoewel er op de korte termijn geen tekorten zijn te verwachten, is het duidelijk dat de huidige manier van omgang met fossiele brandstoffen verre van duurzaam is. Desalniettemin is de zorg over het opraken van natuurlijke grondstoffen afgenomen. Tegelijkertijd zijn er echter andere milieuaspecten van het gebruik van fossiele brandstoffen naar voren gekomen. Vooral van de emissies, die ontstaan bij verbranding van fossiele brandstoffen, wordt aangenomen dat ze grote invloed uitoefenen op het milieu en op de menselijke gezondheid, via de uitstoot van stofdeeltjes, smogvorming, verzuring en klimaatverandering.

Op dit moment wordt klimaatverandering, veroorzaakt door een versterkt broeikaseffect, gezien als één van de grootste milieuproblemen. Zoals beschreven door het ‘Intergovernmental Panel on Climate Change’ (IPCC) van de Verenigde Naties is de concentratie van broeikasgassen in de atmosfeer gedurende de afgelopen eeuw aanmerkelijk toegenomen, wat heeft geleid tot een toename van het broeikaseffect. Deze toename is er hoogstwaarschijnlijk de oorzaak van dat de gemiddelde temperatuur op aarde gedurende de afgelopen eeuw met ongeveer 0,6ºC gestegen. Vooral de toename van de concentratie van kooldioxide (CO_2) in de atmosfeer speelt een belangrijke rol in de toename van het broeikaseffect. Door het verbranden van fossiele brandstoffen en door gewijzigd landgebruik (met name ontbossing) is deze concentratie de afgelopen eeuw snel gegroeid. Bij ongewijzigd

beleid dreigt het broeikaseffect deze eeuw sterk toe te nemen, met als mogelijk resultaat een ingrijpende verandering van het klimaat.

Om deze problemen het hoofd te bieden wordt er gezocht naar maatregelen die tot doel hebben de uitstoot van broeikasgassen te verminderen. Eén van die maatregelen is verdere verbetering van de efficiency waarmee fossiele brandstoffen in onze energieconsumptie worden gebruikt. Een veelheid aan mogelijkheden om deze efficiency te verbeteren is inmiddels geïmplementeerd, terwijl nieuwe mogelijkheden zich aandienen. Echter, door de huidige groei van de wereldbevolking en het stijgende niveau van economische activiteit neemt mondiaal zowel het gebruik van fossiele brandstoffen als de uitstoot van broeikasgassen nog steeds toe. Dit betekent dat nieuwe maatregelen nodig zijn om de productiviteit van fossiele brandstoffen te verhogen en de uitstoot van broeikasgassen te verminderen.

Sinds kort dringt in bredere kring het besef door dat een aanzienlijke vermindering van het gebruik van fossiele brandstoffen en van de uitstoot van CO_2-emissies bereikt kan worden door beter om te gaan met materialen. Als materialen efficiënter zouden worden gebruikt, zouden er ook minder materialen geproduceerd hoeven te worden en zouden er minder grondstoffen gewonnen hoeven te worden. Dit zou betekenen dat er minder energie zou worden gebruikt, minder emissies zouden worden uitgestoten en minder afval geproduceerd zou worden. Voor kunststoffen, de materialen die centraal staan in dit proefschrift, is het verband tussen materiaalgebruik enerzijds en energiegebruik en CO_2-emissies anderzijds erg nauw, omdat kunststoffen geproduceerd worden uit fossiele brandstoffen.

Er zijn veel maatregelen mogelijk om te komen tot vermindering van het energiegebruik en verlaging van CO_2-emissies in het materiaalsysteem. Voorbeelden van deze maatregelen zijn: hergebruik (recycling), afvalpreventie, ‘downgauging’ (het herontwerpen van producten, met als doel minder materiaalgebruik), het verlengen van de levensduur van producten en substitutie (producten vervaardigen uit andere, minder milieubelastende materialen). Omdat implementatie van deze maatregelen vaak niet eenvoudig is, is een grondige analyse nodig van de gevolgen van de verschillende maatregelen, zodat de verschillende maatregelen tegen elkaar afgewogen kunnen worden en zodat weloverwogen beleidskeuzes kunnen worden gemaakt. Vooral voor de meest veelbelovende maatregelen, de maatregelen die het materiaalsysteem structureel veranderen (zoals materiaalrecycling en substitutie) is een gedetailleerde analyse nodig om een inschatting te kunnen maken van de invloed op het totale gebruik van fossiele brandstoffen en de totale CO_2-emissies.

Komen tot een beter begrip van het materiaalsysteem is één van de belangrijkste doelen van het onderzoeksgebied ‘Industriële Ecologie’. Industriële Ecologie is gebaseerd op het concept van ‘Industrieel Metabolisme’. Dit concept benadrukt de analogie tussen biologische

organismen en het economische systeem. Beiden zijn materiaalverwerkende systemen, aangedreven door energie. Een belangrijk verschil is echter dat in het economische systeem nauwelijks grondstoffen worden hergebruikt. De analogie is bedoeld als richtlijn bij het zoeken naar opties om te komen tot een duurzame industriële economie.

De studie van het industrieel metabolisme van materialen wordt aangeduid als 'Material Flow Analysis' (MFA). M.b.v. MFA kunnen opties voor een verbeterd materiaalgebruik worden geïdentificeerd. Door MFA te combineren met een analyse van emissies, is het mogelijk om de gebieden aan te wijzen die speciale aandacht vragen vanuit het oogpunt van preventie van milieuverontreiniging.

De aanpak die gevolgd wordt in dit proefschrift kan als volgt worden samengevat:

- Eerst worden de materiaalstromen van kunststoffen door de maatschappij in kaart gebracht. Dit resulteert in een materiaalbalans van de levenscyclus van kunststoffen.
- Vervolgens worden energie- en CO_2-emissieanalyses uitgevoerd voor alle industriële processen, die in de levenscyclus van kunststoffen worden toegepast voor de productie en verwerking van kunststoffen en de grondstoffen daarvoor, alsmede voor het verwerken van kunststofafval.
- Door de resultaten van de analyses van materiaalstromen, energiegebruik en CO_2-emissies te combineren wordt een volledig overzicht gekregen van het materiaalgebruik, het energiegebruik en de CO_2-emissies, die gerelateerd zijn aan de levenscyclus van kunststoffen.
- Vervolgens worden potentiële maatregelen gedefinieerd, die tot doel hebben om via veranderingen in het materiaalsysteem het materiaalgebruik, het energiegebruik en / of de CO_2-uitstoot te verminderen.
- Tenslotte wordt het effect van deze maatregelen onderzocht, door berekening van de invloed op het totale materiaalgebruik, het totale energiegebruik, de totale CO_2-emissies en de totale kosten van de gehele levenscyclus.

Op grond van deze analyse kunnen conclusies worden getrokken m.b.t. de effectiviteit van de verschillende maatregelen. De verschillende opties kunnen worden beoordeeld en tegen elkaar worden afgewogen, zodat de meest effectieve maatregelen kunnen worden aangewezen.

In hoofdstuk 2 stellen we een nieuwe methode voor om fysieke materiaalstromen door de maatschappij te berekenen. Zoals we hierboven hebben aangeduid is het voor het ontwikkelen van beleid op het gebied van materiaalgebruik en afvalverwerking van wezenlijk belang om inzicht te hebben in het gebruik van materialen in de maatschappij en de materiaal- en afvalstromen die daarmee gepaard gaan. Om het risico van het nemen van sub-optimale beleidsmaatregelen m.b.t. milieuproblemen zoveel mogelijk te beperken, is een integraal overzicht van materiaalstromen door de maatschappij nodig.

Tot nu toe ontbreekt een integraal overzicht van fysieke materiaalstromen door de maatschappij. Het is moeilijk om een integraal overzicht samen te stellen uit verschillende gegevensbronnen, vanwege problemen als onderlinge verschillen in definities, in onderverdelingen van materiaalstromen en in het referentiejaar, waarop de gegevens betrekking hebben. Bovendien zijn gegevens over de finale consumptie van materialen over het algemeen geheel niet voorhanden. Vaak wordt als benadering voor de finale consumptie de ‘apparent consumption’ (schijnbare consumptie) gebruikt. De ‘apparent consumption’ van een bepaald materiaal wordt berekend als de geproduceerde hoeveelheid *plus* de geïmporteerde hoeveelheid *minus* de geëxporteerde hoeveelheid van dat materiaal. Echter, omdat producten vaak bestaan uit verschillende materialen en omdat samen met producten verpakkingsmaterialen worden geïmporteerd c.q. geëxporteerd, is een gedeelte van de materiaalstromen die de landsgrenzen passeren in de statistieken onzichtbaar. Daarom is de ‘apparent consumption’ geen goede maat voor de finale consumptie van een economie.

De in hoofdstuk 2 ontwikkelde methode is genaamd STREAMS. Dit staat voor: ‘STatistical REsearch for Analysing Material Streams’, ofwel ‘Statistisch Onderzoek voor het Analyseren van Materiaalstromen’. Deze methode heeft als doel om de finale consumptie van materialen door de maatschappij te berekenen. De STREAMS-methode is gebaseerd op de statistische gebruik- en aanbodtabellen, die de economie van een land beschrijven in termen van het gebruik en aanbod van materialen, producten en diensten door industriesectoren, dienstensectoren en consumenten. Uit de gebruik- en aanbodtabellen kan informatie worden gehaald over het gebruik en aanbod van materialen en producten door individuele industrieën. Door per industrie in te schatten waarvoor de gebruikte materialen dienen (als verpakking, onderdeel of eindproduct), is het mogelijk om deze materialen toe te wijzen aan de producten die door de betreffende industrie worden geproduceerd en geleverd. Op deze manier kunnen de materialen worden gevolgd op hun weg vanaf de winning van ruwe grondstoffen tot en met het finale gebruik en verder, tot in het afvalstadium.

De STREAMS-methode heeft als voordeel dat vrijwel alle gegevens worden afgeleid van één enkele bron. Verschillen in definities, dwarsdoorsneden, referentiejaren e.d. spelen dus vrijwel geen rol. Het unieke van de methode is dat hij informatie verschaft over het finale gebruik van materialen en producten, informatie die verder niet uit de literatuur te halen is, maar die het meest nauwkeurig de consumptie van materialen in een land weergeeft.

In hoofdstuk 3 wordt de STREAMS-methode getest en toegepast op de kunststofstromen in Nederland in het jaar 1990. Uit de berekeningen komt naar voren dat de finale consumptie van kunststoffen in Nederland in dat jaar ongeveer 1260 kiloton bedroeg. Dit getal blijkt aanzienlijk hoger te zijn dan de ‘apparent consumption’ van ongeveer 1140 kiloton, die eenvoudig te berekenen is uit cijfers over de productie, import en export van kunststoffen in

Nederland. Daaruit concluderen we dat de 'apparent consumption', hoewel gemakkelijk te berekenen, nogal een slechte benadering is voor de finale consumptie.

De analyse van de finale consumptie van kunststoffen in Nederland laat zien dat m.b.v. de STREAMS-methode gedetailleerde informatie verkregen kan worden m.b.t. materiaalstromen in een land in alle stadia van hun levenscyclus. De STREAMS-methode vertoont echter nog een aantal problemen, die opgelost moeten worden om nauwkeurigere resultaten te behalen op de lagere aggregatieniveaus. We schatten dat de gemiddelde afwijking van de resultaten van onze analyse op het laagste aggregatieniveau ± 30% bedraagt. De resultaten op hogere aggregatieniveaus (d.w.z. meer samengevoegde resultaten) zijn beduidend nauwkeuriger. Een deel van de afwijkingen wordt veroorzaakt door factoren die typisch zijn voor Nederland, een relatief kleine, open economie met voor een aantal producten een beperkt aantal producenten. Om te voorkomen dat uit de nationale statistieken informatie gehaald kan worden omtrent de omzet van individuele bedrijven, zijn de leveringen van industrieën, waarin slechts één of enkele producenten actief zijn, niet in de statistieken opgenomen. Een aantal andere factoren met een negatieve uitwerking op de nauwkeurigheid zijn inherent aan de rekenmethode, zoals het feit dat uitgegaan wordt van financiële statistieken, die dus moeten worden omgerekend in fysieke hoeveelheden m.b.v. gemiddelde prijzen. De methode kan nog worden verfijnd door een aantal van deze factoren te verbeteren of te elimineren. Met name de conversie van monetaire naar fysieke eenheden en de manier waarop materialen aan producten worden toegewezen kunnen nog beduidend worden verfijnd, zodat nauwkeurigere resultaten verkregen worden. We verwachten dat door deze verfijningen de gemiddelde afwijking op het laagste aggregatieniveau zal dalen tot ± 15%.

In hoofdstuk 4 wordt onderzocht hoeveel fossiele brandstoffen er in West Europa worden gebruikt – zowel als grondstof als als energiebron – t.g.v. de consumptie van kunststoffen en hoeveel CO_2-emissies er dientengevolge vrijkomen. De hoeveelheid fossiele brandstoffen die gebruikt wordt *als grondstof* wordt bepaald door het opstellen van een materiaalbalans van de West-Europese levenscyclus van kunststoffen. De hoeveelheid fossiele brandstoffen die gebruikt wordt *als energiebron* en de CO_2-emissies in de totale levenscyclus worden afgeleid uit de resultaten van een literatuuronderzoek naar het energiegebruik en de CO_2-emissies van alle belangrijke industriële processen in de levenscyclus van kunststoffen. Daarbij worden meegenomen processen voor grondstofwinning, de productie van alkenen (stoomkraken), de productie van tussenproducten, polymeren en kunststofproducten, alsmede de verwerking van kunststofafval.

Uit onze berekeningen concluderen we dat de West-Europese levenscyclus van kunststoffen in 1994 in totaal ongeveer 2300 PJ aan fossiele brandstoffen gebruikte, 4,4% van het totale West-Europese gebruik van fossiele brandstoffen in dat jaar. Ongeveer 1100 PJ daarvan werd gebruikt als grondstof, de rest als brandstof. De CO_2-emissies veroorzaakt door de West-

Europese levenscyclus van kunststoffen bedroegen ongeveer 80 Megaton, ofwel 2,3% van de totale CO_2-emissies in West Europa in 1994. De grootste bijdragen aan het totale gebruik van fossiele brandstoffen in de levenscyclus van kunststoffen werden geleverd door de productie van polymeren (28%), de productie van alkenen (23%) en de productie van kunststofproducten (18%). Deze processen waren ook verantwoordelijk voor de grootste aandelen in de totale CO_2-emissies van de levenscyclus van kunststoffen: respectievelijk 27%, 17% en 14%.

In hoofdstuk 5 bekijken we welke technologische maatregelen, die leiden tot structurele veranderingen in de levenscyclus van kunststoffen, er genomen kunnen worden met als doel om zowel het gebruik van fossiele brandstoffen als de uitstoot van CO_2 in de levenscyclus van kunststoffen terug te dringen. Van maatregelen die grote delen van de levenscyclus beïnvloeden, zoals het gebruik van alternatieve grondstoffen voor de productie van alkenen (dus het gebruik van alternatieve productieroutes), alternatieve kunststofsoorten (materiaalsubstitutie) of alternatieve processen voor het verwerken van kunststofafval (recycling), is het niet eenvoudig om de effecten te bepalen op het totale gebruik van fossiele brandstoffen, de totale uitstoot van CO_2 en de totale kosten. Een overzicht van alle effecten kan alleen verkregen worden door gebruik te maken van een rekenmodel, dat rekening houdt met alle onderlinge verbanden. In hoofdstuk 5 bespreken we een methode om de invloeden te berekenen van structurele veranderingen in de levenscyclus van materialen op het totale gebruik van fossiele brandstoffen, de totale CO_2-emissies en de totale kosten. We passen deze methode toe op de levenscyclus van kunststoffen in Nederland. M.b.v. deze methode onderzoeken we een serie maatregelen, van het gebruik van alternatieve grondstoffen (inclusief biomassa) tot substitutie tussen verschillende kunststoffen en het gebruik van geavanceerde technologieën voor kunststofrecycling.

In hoofdstuk 5 worden de volgende conclusies getrokken:

- Verschuivingen binnen de traditionele grondstoffen van stoomkrakers (ethaan, LPG, gasolie en nafta) beïnvloeden slechts marginaal het totale gebruik van fossiele brandstoffen en de totale uitstoot van CO_2. Hogere reducties kunnen bereikt worden door het gebruik van nieuwe procesroutes, die uitgaan van biomassa als grondstof: pyrolyse (‘flash pyrolysis’) van biomassa, of het ‘methanol-to-olefins’-proces gecombineerd met de productie van methanol uit biomassa. Vooral door een combinatie van deze twee routes blijkt het mogelijk te zijn om aanzienlijke reducties te bereiken.

- Omdat de mogelijkheden tot substitutie tussen verschillende kunststofsoorten beperkt zijn en omdat de verschillen in energiegebruik en CO_2-emissies bij de productie van de verschillende kunststofsoorten gering zijn, zijn er geen grote reducties te verwachten door

substitutie tussen kunststofsoorten (tenzij daardoor nieuwe, efficiëntere productontwerpen mogelijk zou worden).

- Het is niet mogelijk om tegelijkertijd het gebruik van fossiele brandstoffen te verminderen èn de uitstoot van CO_2-emissies te reduceren door verhoging van het aandeel kunststofafval dat gestort wordt of door verhoging van het aandeel kunststofafval dat verbrand wordt. Hoewel afvalverbranding een goedkoop en eenvoudig toe te passen proces is, is het geen goede optie, omdat het de netto uitstoot van CO_2-emissies verhoogt, zelfs wanneer de vrijkomende energie wordt omgezet in elektriciteit.

- De grootste reducties in het gebruik van fossiele brandstoffen en de uitstoot van CO_2 door maatregelen m.b.t. het verwerken van kunststofafval kunnen worden bereikt door verhoging van het aandeel mechanische recycling, door gebruik te maken van het 'selective dissolution'-proces, of door het injecteren van kunststofafval in hoogovens. Om de weg vrij te maken voor mechanische recycling is het nodig dat aandacht wordt besteed aan het ontwikkelen van geschikte blend- en / of scheidingstechnieken.

- We schatten dat het door structurele veranderingen in de levenscyclus van kunststoffen in Nederland mogelijk is om het gebruik van fossiele brandstoffen met ongeveer 60% te verlagen, gecombineerd met een verlaging van de uitstoot van CO_2 van ongeveer 30%. Dit kan bijvoorbeeld bereikt worden door het op grote schaal inzetten van biomassa als grondstof voor de productie van kunststoffen, eventueel gecombineerd met een verhoging van het aandeel mechanische recycling. Implementatie van deze maatregelen zou evenwel leiden tot een kostenstijging van ongeveer 20%.

Slotopmerkingen

Op grond van het in dit proefschrift gepresenteerde onderzoek kunnen een aantal belangrijke conclusies worden getrokken m.b.t. de analyse van materiaalstromen en de invloed die het gebruik van materialen heeft op klimaatverandering, alsmede m.b.t. het onderzoek naar de mogelijkheden tot reductie van het gebruik van fossiele brandstoffen en de uitstoot van CO_2.

Een beter begrip van materiaalstromen door de economie is essentieel voor de ontwikkeling van effectieve strategieën voor een duurzaam beheer van productketens (levenscycli). Zonder dit begrip is de kans groot dat beleidsmaatregelen worden geïmplementeerd, die niet resulteren in het verwachte resultaat of die onvoorziene (economische) gevolgen hebben. Zo hangt het milieutechnisch en economisch optimale beheer van afvalstromen in de economie bijvoorbeeld af van een goede inschatting van de consumptie van materialen en de grootte en samenstelling van de verschillende afvalstromen. Ons onderzoek bewijst dat voor een open economie, zoals de Nederlandse, 'apparent consumption' een slechte maat is voor het finale

gebruik van materialen. In een wereld waarin regionale en nationale economieën zich steeds meer openen voor internationale handel, wordt de behoefte aan adequate maatregelen m.b.t. de consumptie van materialen steeds belangrijker.

In dit proefschrift hebben we een methode ontwikkeld om nauwkeurig de materiaalstromen door de economie te bepalen en we hebben deze getest m.b.v. statistische gegevens over het gebruik van kunststoffen in Nederland. Deze analyse toonde aan dat het werkelijke finale gebruik van kunststoffen in Nederland hoger is dan tot nu toe werd aangenomen op grond van de 'apparent consumption' in de statistieken. Dit heeft gevolgen voor het afvalbeleid en voor de te volgen strategieën voor de reductie van de uitstoot van CO_2. De toekomstige hoeveelheden kunststofafval zullen bijvoorbeeld waarschijnlijk groter zijn dan tot nu toe werd aangenomen, wat, gezien de huidige nadruk op afvalverbranding in het Nederlandse afvalbeleid, zal leiden tot een verhoogde uitstoot van CO_2.

Een volledig overzicht van materiaalstromen in de samenleving maakt een geïntegreerd onderzoek mogelijk naar opties ter vermindering van de uitstoot van broeikasgassen en / of opties ter verbetering van de energie-efficiency. M.b.v. kennis over materiaalstromen kunnen verschillende maatregelen in verschillende stadia van de levenscyclus van producten of materialen tegen elkaar worden afgewogen. In dit proefschrift vergeleken we bijvoorbeeld maatregelen die ingrijpen op het gebruik van grondstoffen, op de samenstelling van producten en op de verwerking van afval, met als doel om de invloed te bepalen op de totale uitstoot van broeikasgassen en het totale gebruik van fossiele brandstoffen.

Op grond van onze analyse hebben we een aantal gebieden gevonden voor toekomstig onderzoek:

- Het verbeteren van de nauwkeurigheid van de resultaten van de STREAMS-methode op lagere aggregatieniveaus. In dit proefschrift hebben we een aantal suggesties gedaan ter verbetering van de STREAMS-methode. Verdere verbeteringen hangen nauw samen met de kwaliteit en het detailniveau van de statistische gegevens die ten grondslag liggen aan de STREAMS-methode. Daarom benadrukken we ten zeerste het belang van nauwkeurige statistische dataverzameling op gedesaggregeerd niveau.

- De STREAMS-methode levert een 'snapshot' van materiaalstromen in een bepaald jaar. De methode zou kunnen worden uitgebreid tot een dynamische methode, die gebruik maakt van historische gegevens voor meerdere jaren. Daardoor wordt het mogelijk om de accumulatie en de levensduur van materialen in de economie te onderzoeken en kunnen toekomstige materiaal- en afvalstromen worden voorspeld. Op die manier kan o.a. een betere inschatting worden gemaakt van toekomstige afvalhoeveelheden en -bronnen. Omdat een dergelijke methode waarschijnlijk nogal arbeidsintensief zal zijn, kan men zich

het best beperken tot die materialen, die een sleutelrol spelen vanuit het perspectief van het beheersen van afvalstromen en / of broeikasgasemissies.

- Een dynamische analyse van materiaalstromen kan tevens helpen bij het vergaren van kennis omtrent consumptiepatronen in de economie. In die zin kunnen dynamische analyses van materiaalstromen worden geïntegreerd in modellen voor het voorspellen van het toekomstig energiegebruik en de toekomstige emissies van broeikasgassen, waardoor de betrouwbaarheid van de voorspellingen wordt verhoogd. Tevens wordt het daardoor mogelijk om afwegingen te maken tussen opties in het materiaal- en energiesysteem. Het werk aan het MATTER-model, waarvoor de resultaten van dit proefschrift zijn gebruikt, is een eerste belangrijke stap in deze richting.

- Tenslotte moet de integratie van de analyse van materiaalstromen in het beleid worden versterkt, vooral in het beleid m.b.t. afvalverwerking en broeikasgasemissies. Hoewel technologische modellen daarbij kunnen helpen, is verder onderzoek nodig naar de socio-politieke aspecten van materiaalgebruik en naar de manier waarop het beleid kan worden gestuurd in de richting van een milieukundig en economisch duurzame ontwikkeling.

Abbreviations and Formulae

ABS	Acrylnitril Butadiene Styrene copolymer
A_{cc}*	Allocation table of core materials and products used as component (Chapter 2)
A_{cp}*	Allocation table of core materials and products used as packaging (Chapter 2)
APME	Association of Plastics Manufacturers in Europe
BTF	Back to feedstock
BTX	Steamcracker fraction consisting of Benzene, Toluene and Xylenes
BUWAL	Bundesamt für Umwelt, Wald und Landschaft
C4	Steamcracker fraction containing butenes and butadiene
CaO	Calcium Oxide
C_{cc}*	Core materials and products contents table, use as component (Chapter 2)
C_{cp}*	Core materials and products contents table, use as packaging (Chapter 2)
CBS	Centraal Bureau voor de Statistiek / Statistics Netherlands
CDU	Crude distillation unit
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Dfl.	Dutch Guilders
DMT	Dimethyl therephtalate
DSD	Duales System Deutschland
ECN	Netherlands Energy Research Foundation
ECU	European Currency Unit
EDC	Ethylene dichloride
EPS	Expanded polystyrene
exp.	Exports
GEMIS	Gesamt-Emissions-Modell Integrierter Systeme
GER	Gross Energy Requirement
GHG	Greenhouse Gas
GJ	Gigajoule (= 10^9 Joule)
GJ_e	Gigajoule electricity
GPPS	General purpose polystyrene
H_2O	Water
HCl	Hydrochloric acid
HDPE	High Density Polyethylene
HHV	Higher Heating Value
HIPS	High impact polystyrene
hp	High pressure
I_{cc}*	Indirect final consumption table, use as component (Chapter 2)
I_{cp}*	Indirect final consumption table, use as packaging (Chapter 2)

IE	Industrial Ecology
imp.	Imports
IPCC	Intergovernmental Panel on Climate Change
J	Joule
kJ	Kilojoule (= 10^3 Joule)
ktonne	Kilotonne (= 10^3 metric tons = 10^6 kg.)
LCA	Lifecycle Analysis
LDPE	Low Density Polyethylene
LHV	Lower Heating Value
LLDPE	Linear Low Density Polyethylene
lp	Low pressure
LPG	Liquefied Petroleum Gasses
MARKAL	MARKet ALlocation
MATTER	MATerials Technologies for CO_2 Emission Reduction
MDI	Diphenylmethane diisocyanate
MFA	Material Flow Analysis / Material Flow Accounting
mil.	Million
mp	Medium pressure
MPW	Mixed plastic waste
Mtonne	Megatonne (= 10^6 metric tons = 10^9 kg.)
MTO	Methanol-to-olefins
NaOH	Sodium Hydroxide
N_2O	Nitrous oxide
NFK	Dutch Federation for Plastics
O_2	Oxygen
PA	Polyamide
PE	Polyethylene
PET	Polyethylene Therephtalate
PJ	Petajoule (= 10^{15} Joule)
PMMA	Polymethyl Methacrylate
PP	Polypropylene
PS	Polystyrene
PTA	Therephtalic acid
PUR	Polyurethane
PVC	Polyvinyl chloride
RDF	Refuse Derived Fuel
RIVM	National Institute of Public Health and Environmental Protection
S	Supply table (Chapter 2)
S_c	Core supply table (Chapter 2)
S_c*	Physical core supply table (Chapter 2)

S_{goods}	Goods supply table (Chapter 2)
$S_{goods, perc.}$	Percentage goods supply table (Chapter 2)
SAN	Styrene Acrylonitrile copolymer
SBR	Styrene Butadiene Rubber
SFA	Substance Flow Analysis
STREAMS	STatistical REsearch for Analysing Material Streams
t	Tonne (metric tons)
TDA	Tolylene diamine
TDI	Tolylene diisocyanate
U	Use table
U_c	Core use table (Chapter 2)
U_c*	Physical core use table (Chapter 2)
U_{cc}*	Physical core use table, use as component (Chapter 2)
U_{cf}*	Physical core use table, use as final product (Chapter 2)
U_{cp}*	Physical core use table, use as packaging (Chapter 2)
U_{goods}	Goods use table (Chapter 2)
$U_{goods, perc.}$	Percentage goods use table (Chapter 2)
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
UNCED	United Nations Conference on Environment and Development
VCM	Vinylchloride Monomer
VNCI	Association of the Dutch Chemical Industry
WCED	World Commission on Environment and Development
wt.%	Weight percent

200

Curriculum Vitae

Louis Joosten werd geboren in Veghel (N.Br.) op 15 juni 1968. In 1986 behaalde hij het VWO-diploma aan het Kruisheren Kollege te Uden. Vervolgens studeerde hij Werktuigbouwkunde aan de Technische Universiteit Eindhoven. In 1991 studeerde hij af bij de vakgroep Werktuigbouwkundige Productietechnologie en Automatisering (WPA) bij prof. ir. J.A.G. Kals op het onderwerp “De ductiliteit van materialen bij hulsextrusie en duntrekken”. Hij behaalde daarbij het doctoraaldiploma “met grote waardering”.
Na een vervolgstudie milieukunde aan de Hogeschool Enschede, die werd afgesloten met een studie naar de invloed van duurzaam bouwen op materiaal- en energiestromen, is hij in 1994 in dienst gekomen als assisent-in-opleiding (AIO) bij de vakgroep Natuurwetenschap en Samenleving van de Universiteit Utrecht. Daar werkte hij aan een studie naar materiaal- en energiestromen in de levenscyclus van kunststoffen. In het kader van dit onderzoek was hij o.m. betrokken bij het MATTER-project, uitgevoerd door een samenwerkingsverband van het Energieonderzoekscentrum Nederland, de Rijksuniversiteit Groningen, de Universiteit Utrecht, de Vrije Universiteit en het bureau Brand- en Grondstoffen. Doel van dit project was het bepalen van de impact van veranderingen in het materiaalsysteem op de uitstoot van broeikasgasemissies.
Sinds 1999 is hij als procestechnoloog werkzaam in de industriële automatisering bij KSE in Bladel.

Dankwoord

En dan ligt het er, een voltooid proefschrift… En hoewel misschien geen levenswerk, toch is het het resultaat van – inclusief onderbrekingen – zeveneneenhalf jaar werk. Zeveneneenhalf jaar heb ik dit proefschrift met me meegedragen. Dat is niet altijd even gemakkelijk gegaan, maar nu is het er dan. Tijdens het schrijven van dit proefschrift heb ik veel geleerd, niet alleen in wetenschappelijk opzicht, maar vooral ook wat betreft het opdoen van levenservaring, mensenkennis, zelfkennis en sociale vaardigheden. Al met al een turbulente, maar waardevolle periode.

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